NASA TECHNICAL NOTE

NASA TN D-2569

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NASA TN D-2569

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1965

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SUMMARY

Various types of single-axis pilot-controlled nonlinear outputs have been matched by a linear model plus a nonlinear element. Measured gains from this method have been obtained and for the linear regions of control, the closed-loop characteristics were computed. The results show that in general the pilot does not change his measured gains in direct proportion to the changes made in the nonlinear control characteristics. Minor variations in his gains do occur, however, and these variations imply some change in control technique. This change appears to be the result of an attempt to maintain reasonable performance. The pilot does appear to reach a point, at very low saturated control torque values, where his control technique is abruptly changed and a corresponding change in the measured gains results.

An attempt has also been made to apply data from the single-loop problem to a more complicated multi-loop problem in which the control from an outer loop is dependent on an inner-control loop. It was demonstrated that the single-axis single-loop results, with some modification, could be applicable to a multi-loop simulation.

INTRODUCTION

A method of determining pilot-control characteristics has been devised in which the measured parameters are obtained from a mathematical model of the pilot. The analog pilot is made to match or duplicate the pilot's output by an automatic model-adjusting technique such that a representative transfer function of the pilot is obtained. This technique is derived and explained in references 1 and 2.

The results were obtained from the transfer functions of human pilots while they were operating in the control loop. References 1 and 2 present results obtained in experiments in which all the elements of the control loop were linear. In the present investigation the same procedure has been used to determine the effect of including certain nonlinearities in the torque-producing element of the system. These nonlinearities are torque limits and on-off control torques. The nonlinearities are typical of those often found in spacecraft.

In applying the model-matching technique in those cases where the nonlinearity is present as the only available pilot-ouput signal, a similar nonlinearity is included in the linear model used in references 1 to 4. The matching is done by adjusting the gains of the linear section of the model in a manner similar to that of references 1 and 2.

Three different tasks were performed. In one task the maximum simulated torque output of the control stick was limited although the stick was allowed freedom of movement beyond these limits. In the second task the travel of the stick was limited to produce the nonlinearity. On-off control was used in the third task. The value of the torque-output was varied systematically in each of the three tasks. Six experienced test pilots and two engineers were used as subjects.

The measured transfer-function gains together with the derived closed-loop characteristics for the linear system are presented in this paper as well as the response to step inputs for the nonlinear system.

The measured gains from these experiments were used in a multi-loop problem to determine whether these gains are applicable to this type of study. The multi-loop problem consists of a simplified representation of a lunar-landing maneuver.

SYMBOLS

A	model feedback gain, lag break-point frequency, radians/sec
D	stick displacement or voltage representation of stick displacement
I	input to analog pilot
K	general gain
K_1,K_2	particular model gains
s	Laplace operator
V	output of nonlinearity, volts
X_i	desired vehicle displacement, ft
X_o	actual vehicle displacement, ft
α	output of dynamics
δ	output of analog pilot
ζ	damping ratio
θ_i	desired vehicle tilt, deg

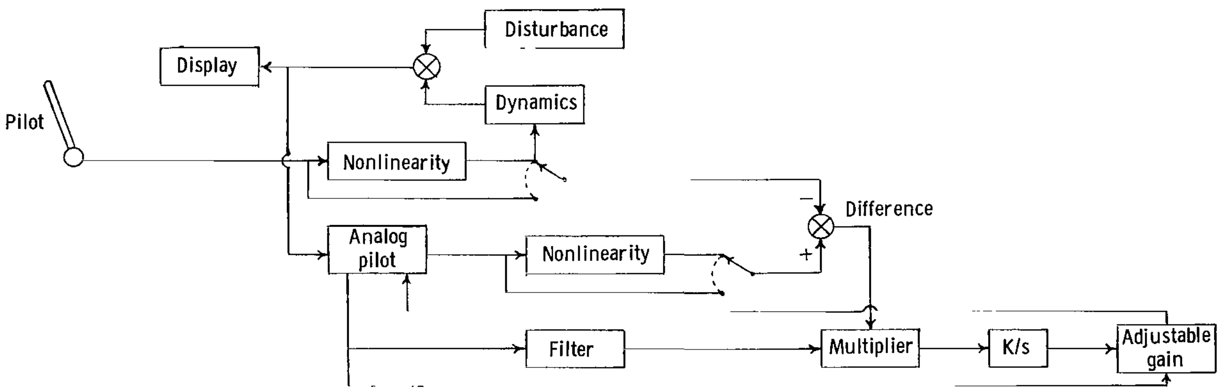
θ_o actual vehicle tilt, deg

ω_n undamped natural frequency, radians/sec

PROCEDURE AND APPARATUS

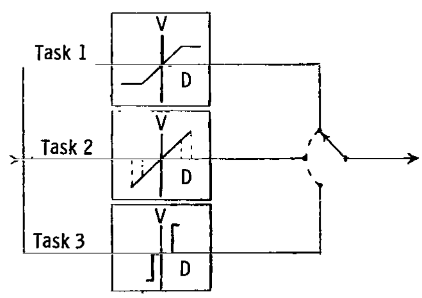
Description

Block diagrams of the elements used in the nonlinear experiments are shown in sketches (a) and (b). Sketch (a) shows the block diagram for the analog pilot of the form $\dfrac{K_1A\left(1 + \dfrac{K_2}{A}s\right)}{(A + s)^2}$ and, sketch (b) shows the nonlinearities for tasks 1, 2, and 3.



Analog-pilot form $\dfrac{K_1 A\left(1 + \dfrac{K_2}{A} s\right)}{(A + s)^2}$

Sketch (a)



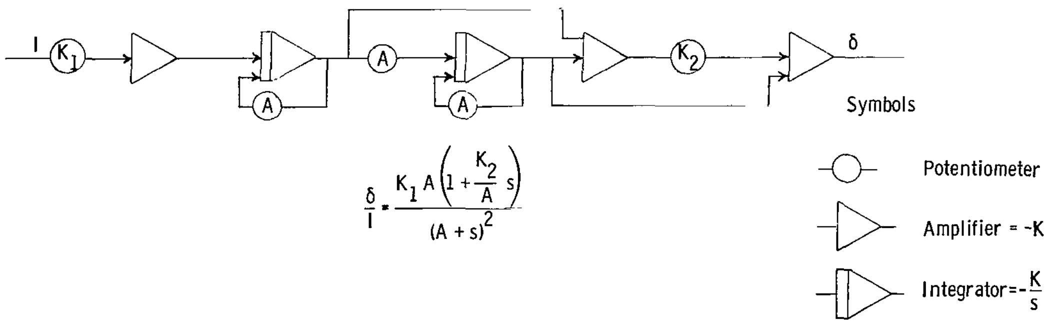
Nonlinearities

Sketch (b)

The simulator shown in figure 1 was a fixed-base single-axis chair similar to the one used in reference 2. The error signal was displayed to the pilot on an oscilloscope as a compensatory task; that is, the horizontal beam of the oscilloscope was deflected vertically by a summation of both the disturbance and the output of the vehicle dynamics. The pilot was told to use his control to keep the beam as near as possible to a fixed reference line. The oscilloscope sensitivity was 5 volts per inch, and the disturbance and control inputs were such that the deflection usually would not exceed ±2 inches from the center line of a 5-inch oscilloscope with a human pilot in the control loop. A few exceptions to this case were encountered when the pilot was operating with low control power in which case the beam would occasionally go off the oscilloscope.

Control was imparted to the vehicle by a centrally located, lightweight control stick. The distance from the top of the stick to the pivot was 15 inches. The maximum displacement of the top of the stick was 3 inches, forward and backwards, which corresponds to a pivot angle of 11.3°. A force of 2.5 pounds was required in order to attain maximum displacement. A linear potentiometer was connected to the base of the stick and transmitted a maximum voltage of ±10 volts to the computer circuitry.

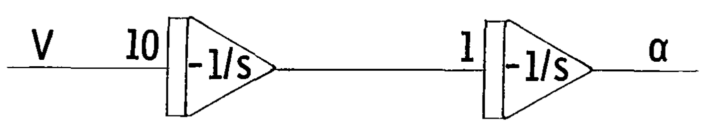
The form of the model used is the same as that used in references 1 and 2 $\left(\frac{\delta}{I} = \frac{K_1 A\left(1 + \frac{K_2}{A}s\right)}{(A + s)^2}\right)$, and is presented in the following computer diagram notation:



Sketch (c)

The automatic gain-adjustment feature of the analog pilot is shown in block-diagram form in sketch (a). Reference 2 gives the derivation as well as the computer diagram of the analog pilot and its associated adjustment elements. Sketch (a) outlines the adjustment mechanism for one gain only. The other two gains were mechanized in like fashion so that all three gains could adjust at the same time.

The dynamics of the vehicle for all tasks was $10/s^2$. This dynamics represents an inertia system with no damping. The computer diagram for the dynamics is:



Sketch (d)

where $\frac{\alpha}{V} = \frac{10}{s^2}$.

The disturbance, or forcing function, was inserted in the loop to provide a suitable work load. This disturbance was obtained from a Gaussian noise generator filtered with two first-order, low-pass filters with suitable break-point frequencies. Preliminary tests showed that a disturbance with a break-point frequency of 0.5 radian per second would not be suitable in the present investigation. (See ref. 2.) With the low saturation limits that were to be used in the present investigation, the vehicle acceleration was not high enough to enable the pilot to maintain effective control. To provide a more suitable task and still require decisive control motion, the break-point frequency and amplitude of the disturbance were changed. The break-point frequency was reduced to 0.125 radian per second, and the amplitude was set so that disturbance amplitudes as large as ±200 volts would occur. Analytically, these changes represent approximate maximum accelerations in the disturbance of ±3 volts per second per second $\left(200(0.125)^2\right)$. This input disturbance produced situations in which the pilot was required at times to keep the control on the limit for as long as 2.5 seconds for the most restricted case. With a 1-volt stick output limit and vehicle dynamics of $10/s^2$, the maximum vehicle acceleration was 10 volts per second per second.

Operation

Three distinct tasks were performed with the simulator. Although each task differed with respect to the intermediate stick output, each had some form of limit on the maximum output. A limit on the stick-output voltage simulates a limit on the vehicle-control torque, which in turn places a limit on vehicle acceleration for the simulated vehicle dynamics used in these tests. The first task consisted of a set of runs in which the pilot had complete freedom in stick deflection but with the maximum voltage output systematically reduced from run to run. The slope of the curve defining the variation of voltage output with stick deflection remained constant up to the prescribed maximum voltage (task 1, sketch (b)) where the maximum voltage was maintained as long as the stick deflection was greater than that required to produce this voltage. The maximum voltage was varied from ±10 volts down to ±1 volt for a sequence of runs. In this task it is possible to have the analog model match either the pilot's stick output or the limited output from the nonlinear element. Preliminary tests using each of these signals resulted in an agreement of the gain measurements obtained. Because the most rapid gain adjustment was obtained by matching the stick output with the linear analog-pilot output, this method was chosen rather than the one incorporating the nonlinear element.

In the second task, the variation in the runs consisted of actually putting a limit on the stick deflection so that the slope of the voltage output remained constant up to the point where the stick was limited. Here again the limit was varied from ±10 volts down to ±1 volt. In this case it was necessary to place a limit on the output of the linear analog pilot which corresponded to the maximum output allowed the pilot and then to match the two signals. The two tasks are forms of a linear saturated system.

For the third task pilot control was imparted to the vehicle dynamics by means of an on-off system. Only a slight deflection of the stick, $\pm 1^{\circ}$, was required to turn on a preset step voltage. Maximum deflection, approximately $\pm 1.5^{\circ}$, was fixed by the amount of leeway in the switch activator. Matching was done by comparing the on-off outputs of the pilot and analog pilot. The model was constructed with an arbitrarily selected switching voltage (that is, voltage where the analog pilot switches in the control step voltage) placed at the output of the linear analog model. When the output exceeded the switching voltage, a preselected simulated torque output equal to that provided the pilot was produced. The on-off signals from the pilot and from the analog model were compared to provide the difference signal needed for the automatic model-adjustment calculations. The results obtained by matching stick output were poor. Apparently, the pilot moved the stick within the dead space in a manner that did not correlate with the error. Only his contact with the control switch was made in a consistent manner. Consequently, the on-off output was used for matching.

In all three tasks, the pilots were tested down to the minimum value of the saturated or on-off voltage at which he could maintain control. In most cases this minimum value was ±1 volt. Only one subject was able to maintain control with ±0.5 volt. In other cases it was necessary to adjust the disturbance characteristics somewhat to allow for completion of tests with a ±1-volt lower limit.

RESULTS AND DISCUSSION

General Results

Results for all the individual pilots are presented in table I. Sample time histories of $1\frac{1}{2}$ minutes taken from 3-minute runs are presented in figures 2 to 13. These time histories illustrate the close match achieved between the human-pilot and the analog-pilot output.

Table I presents the average measured gains and the closed-loop characteristics obtained by using these gains. The dynamic characteristics of the closed-loop system are predominately oscillatory and are presented in terms of the frequency and the damping ratio and two first-order characteristics, which are presented in terms of real roots. The values given for the real roots are the break-point frequencies of the first-order characteristics. These first-order characteristics would be considered the dominant characteristics only if the real roots were much lower than the frequency of the oscillatory characteristic. The static error, which is equivalent to the switching voltage $\left(\frac{2.5}{K_1/A}\right)$, is presented for the third task in table I. The root mean square of the displayed error is also presented for several pilots and is used as a generalized error criteria of pilot performance. The values presented were obtained from the complete runs. A low root-mean-square error indicates good tracking.

Task 1.- With the simulated torque-output limit set at ±10 volts, task 1 was completely linear; that is, in no instance did any of the subjects reach the limit. The tests were repeated with progressively lower limits until the subject was no longer able to maintain control. Although there were some small changes in the measured gains, these changes were never in direct proportion to the change in the control-torque limit. For some of the subjects the small variations that did occur after the limits of the clipped voltage, which produced the limits in control torque, were reached consisted of a slight reduction in A and/or a slight increase in K_2. (See table I.) The combined changes in A and K_2 caused the frequency to increase and the damping ratio to decrease. Furthermore, the values of the real roots had a tendency to separate even more. The other subjects showed no definite variation in A or K_2 and thereby showed no definite variation in the closed-loop characteristics.

The closed-loop characteristics with low-limit voltages are analytically fictitious because they are obtained from a linear analysis whereas the system is actually nonlinear when the lowest limits are imposed. Therefore, the calculated closed-loop frequencies cannot be observed in the error time histories. These closed-loop frequencies are presented in order to illustrate the effect of the changes in the linear analog pilot.

A large decrease in the measured gain K_1 occurred in one instance during the last portion of the test with pilot B. (See fig. 4.) This decrease appears to be the same type of change in control technique that occurred with pilot D for task 2 (fig. 11), which is discussed later. The measured gains for pilot B taken both before and after this change are presented for task 1 in table I(a).

The preceding discussion of task 1 would not be complete without a brief description of the various piloting techniques used for the control task. Pilot B, for example, began reaching the limits of the clipped voltage at ±5 volts (fig. 2), and at ±2 volts (fig. 3) was also using the physical stick limits even though the maximum voltage output was clipped at the 2-volt lower level. Pilot A, engineer G, and engineer H operated in a similar fashion.

The output of pilots D and J was such that they did not start using the limits of the clipped voltage until about ±2 volts. Therefore, for pilots D and J, the runs with ±10 volts, ±5 volts, and ±3 volts were essentially the same. This result is substantiated by the values of the gains and the root-mean-square error values obtained during the runs. These values are presented in table I. Pilot K operated in a slightly different manner, in that he operated with a self-imposed step-like stick-deflection limit of about ±2 volts; that is, he would control his stick so that he would have a step-like output of ±2 volts even though he had access to a larger output. This ±2 volts was not the maximum of a linear output as in the case for pilots D and J.

Limiting only the acceleration resulted in a different effect on the pilot than that from limiting both acceleration and velocity. Presented in reference 2 are tests in which the simulated vehicle control sensitivity was reduced while using a dynamics of $\frac{K}{s(s + 1)}$. This condition resulted in a reduction of both system acceleration and steady-state velocity for a given stick deflection. In the tests of reference 2, the pilot adjusted his K_1 gain in proportion to the change in vehicle-control sensitivity to maintain constant system characteristics. In the present tests in which vehicle-control sensitivity was held constant and system maximum acceleration reduced, the system maximum velocity was in no way restricted. In these tests there were no changes in pilot gains that were in direct proportion to the reduction in maximum acceleration. It is quite likely that in the simulation of a vehicle with damping augmentation, some given vehicle-control sensitivity, and a given maximum system velocity (established by the amount of rate feedback), an experimental reduction in maximum acceleration for the system (established by placing a limit on the simulated torque output as was done in the present investigation) would result in significant changes in the K_1 gains of the pilot. However, the accuracy of this assumption would have to be determined by further tests.

Task 2.- Results obtained for task 2 were more variable than those obtained for task 1. (See table I.) This variation is probably a reflection of the fact that there is less information available for obtaining the difference signal used in the gain-adjustment loops. The only information available is the signal from the stick in the proportional region of control. The control loops of tasks 1 and 2 are identical in every way except for the freedom of movement of the stick. The conclusions drawn from task 2 are the same as those drawn from task 1; that is, the pilot's gains are not significantly changed by the limit put on the simulated torque output. A notable exception to this general conclusion is the large reduction in K_1 obtained in the test with pilot D for the 1-volt limit in task 2, figure 11 (comparable to pilot B in task 1). The pilot commented that during this run he felt he could not satisfactorily control the displayed error and decided instead to keep the rate of change of the error at a minimum. At this point the measured K_1 dropped rapidly and K_2 increased slightly. Both sets of gains are presented for this run in table I(b).

Again the time histories showed that the pilots varied their control technique. Where pilot A, pilot B, and engineers G and H were reaching the stick limits as early as ± 5 volts and ± 3 volts, pilot D did not begin to use the stick limits until they were lowered to ± 2 volts (fig. 10). Pilot J only used the limits at ± 2 volts occasionally and pilot K again resorted to the self-imposed step limits of ± 2 volts for preset limits greater than ± 2 volts.

Task 3.- In task 3 there are no significant trends of change in gain measurement as the on-off torque value is decreased. The only changes are a small increase in K_2 and a small decrease in A as the step voltage is decreased. Pilot B showed a large variation in A but this variation is accompanied by a change in disturbance amplitude. The trend for a particular disturbance remains the same.

All three tasks at the 1-volt level are practically identical. That is, in tasks 1 and 2 with the 1-volt limit, the control technique approximates an on-off control system in that the control does not dwell in the proportional region of control. In general, the measured values for A and K_2 are in good agreement for each pilot for the three tasks at this control level. The one exception is pilot J, who has a higher value for A in tasks 2 and 3 than in task 1.

Because of the similar nature of the tasks at the 1-volt control level, and since the values of A and K_2 are in good agreement for each of the three tasks for all but one of the pilots, the technique used to evaluate the pilot transfer functions is considered to be sufficiently accurate.

The measured K_1 gain in task 3 has no meaning except when it is considered in conjunction with the arbitrarily selected switching value of 2.5. A physical significance can be given to the K_1 value measured in task 3 by calculating the corresponding static error equivalent to the switching value of the analog pilot. The static error is the minimum displayed error, a zero rate of change being assumed, for which the pilot puts in a correction signal. The static error is approximately equal to the amplitude of the displayed-error time history. This static error is given by $\frac{2.5}{K_1/A}$. These static errors are fairly constant or increase only slightly for increased simulated torque output. The static error of task 2 which corresponds to that of task 3 is equivalent to a full-torque output of 1 volt and is determined by $\frac{1}{K_1/A}$. These values for task 2 are in good agreement with those obtained in task 3 for each pilot. All the subjects had values of error near 3 but pilot B and engineer H, who had error values less than 1.5. A value of 3 corresponds to an oscilloscope displacement of 0.6 inch from the center line. Pilot D had a large static error in task 2, but this error resulted from the method of control he exercised, as was explained earlier. In order to show the response of the nonlinear output of the analog pilot better, a task 3 run with engineer G was made with an expanded time scale. Figure 14 shows part of this run in which the step-voltage output was ±2.5 volts.

Displayed Error Measurements

The measured root mean square of the displayed error was determined and showed a definite increase for each subject measured in task 1 as the limit on the voltage was decreased beyond the point where the subject had reached these limits in attempting further control of the vehicle. In task 2, all the pilots except pilot J showed a significant increase in their root-mean-square error as the limits were decreased. It should be noted, however, that pilot J also had the smallest root-mean-square error for ±1 volt in task 1. In general, the results from task 3 show a decrease in the root-mean-square error followed by an increase as the step inputs were decreased. The significant decrease in the root-mean-square error for pilot B in task 3 resulted from a decrease in the amplitude of the noise input.

An inspection of figures 4 and 9 shows that a large variation in root-mean-square value of the disturbance exists between runs and that the disturbance did not always have an average value of zero. This variation is a result of the comparatively short time of the run compared with the low noise-break frequency. However, this large difference in disturbance from run to run did not affect the root-mean-square error of the system. For example, the root-mean-square value of the displayed error was 3.74 for pilot B (fig. 4) whereas for pilot D it was 3.6 (fig. 9). Because the root-mean-square value of the disturbance varied considerably from run to run, and since this variation did not seem to affect the root-mean-square value of the displayed error, the values of the root mean square of the disturbance were not presented.

Comparison of a Human Pilot and an Analog Pilot in the Loop

As a critical check of the validity of the model, the analog pilot was placed in the loop in place of the human pilot, and a time history of the displayed error was obtained that could be compared with that obtained for the pilot. Runs for which a record of the disturbance had been made on magnetic tape were used to obtain a direct comparison of the human pilot and the analog pilot. Figures 15 and 16 show the variation existing between pilots A and L and their corresponding analog pilots in the control loop. The gains of the analog pilot were obtained from runs made with pilots A and L with the same disturbance time history.

It can be seen that the amplitude of the displayed error obtained with the analog pilot in the loop compares satisfactorily with that obtained for the human pilot. In many instances even the wave shape is in good agreement. The root-mean-square values of the displayed errors are presented in table II and the agreement is also satisfactory. The data from tables I and II for pilot B were from different tests. The root-mean-square error for the analog pilot in the loop in most cases is slightly smaller than that for the human pilot. Similar agreement was obtained for the linear systems presented in reference 3.

To illustrate further the significance of the model gains, the responses to step disturbances with the analog pilot in the loop were obtained for both the on-off and the linear saturated situations. The response to step disturbances in the linear saturated situations can be compared with the calculated closed-loop characteristics of the linear model. However, the test responses were obtained with the limit placed on the output of the linear model. These results are shown in figures 17 and 18. Figure 17 shows the closed-loop system responses, with gains measured for pilot B, to a step disturbance for task 1 and task 2 with a ±1-volt limited output. The response to task 3 is shown for ±3 volts, ±2 volts, and ±1 volt. Figure 18 illustrates similar responses using the gains obtained from pilot D. The measured gains used in determining these responses were taken during a continuous disturbance input and therefore do not necessarily apply for a step disturbance. The responses to the step disturbance are included in this paper to illustrate the effect on the closed-loop characteristics resulting from the changes in the measured gains and limit values. For example, the response characteristics for task 3 showed a change in the frequency of the limit cycle that resulted from the reduction in the control-limit voltage. This decrease in frequency with reduction in the limit voltage was, in general, obtained with the measured gains of all the other pilots.

Effect of Disturbance Characteristics

As mentioned previously, the disturbance characteristics used in the present investigation were different from those used in reference 2; in this investigation the break-point frequency was reduced and the amplitude increased. To illustrate the effect that these changes had on pilot operation, the linear control case (task 1; ±10-volt limit) can be compared with the similar tests in reference 2. (See the $10/s^2$ dynamics in table I of reference 2.) The subjects taking part in both experiments were pilots A, B, and C, and engineers G and H. In general, the measured gains for the two sets of data are in good agreement, and the closed-loop characteristics are almost identical. The largest difference in the closed-loop characteristics for the two sets of data was the slight increase in frequency that occurred in the present investigation. For example, the closed-loop frequency for subject B in the present investigation (task 1; table I(a)) was 3.18 radians per second, and in table I(b) of reference 2, it was 2.5 radians per second.

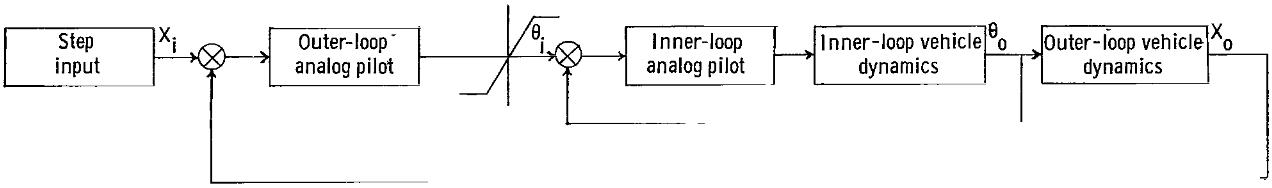
Only subject A showed a consistent reduction in the model gain A and in the closed-loop damping ratio in the present tests as compared with results obtained in reference 2. (The symbol τ in references 1, 2, and 4 is A in this report.) In the interim between experiments, subject A changed from an active piloting job to an executive position, which may account for this change in performance.

Multi-Loop Simulation

A preliminary attempt to apply these single-axis, single-loop data to a multi-loop problem has been made. The multi-loop problem considered is a simplified representation of the lunar landing maneuver presented in reference 5. Translation of the vehicle was accomplished by rotating the vehicle and the lifting engine; thus the desired horizontal thrust component is provided. In the simulation of the problem, the rotation of the vehicle was presented to the pilot as a rotation of a small meter needle. The meter was mounted on an XY plotter and the movement of this meter provided the horizontal and vertical translational information. The pilot had control of both vehicle rotation and thrust magnitude.

It was observed in these tests that all the pilots limited the rotation angle (bank angle) to approximately 30° from the vertical. The general characteristic of the translation response was to have an overshoot occur. Since the pilots were constrained to land as quickly as possible to conserve fuel, a translation error was generally accepted as a trade-off.

In order to restrict the problem to a degree of complexity suitable for a preliminary investigation, only the horizontal translation was considered. It was assumed that the engine thrust was set at the value for hover (1/6 earth gravity) and did not vary. A limit of 30° was applied to the bank angle command to comply with the observed performance in the piloted tests of the problem. A block diagram of the analytical representation showing the two control loops in which the measured transfer functions of the pilot are included is presented in sketch (e). The inner loop, which controlled the rotation of the vehicle, includes a vehicle dynamics of $10/[s(s + 1)]$. The K_1, A, and K_2 gains used in this analog pilot, taken from reference 2, are 2, 6, and 9. The outer loop which controls the horizontal translation and operates in a linear saturated mode includes vehicle dynamics of K/s^2 and pilot gains taken from data presented in table I(g).



Sketch (e)

The first step in applying the measured gains from the single-loop tests to the multi-loop problem was to adjust the K_1 gain for the outer loop so that the product of K_1K would be equivalent to that used in the single-loop nonlinear tests and thereby provide the same closed-loop characteristics in each case. No adjustment was necessary in the case of the inner control loop because the control power (that is, the numerator) of the vehicle was approximately the same in the single-axis tests and the multi-loop problem. The use of the single-loop nonlinear gains in the outer loop however did not provide a suitable reproduction of the time history obtained for the pilot. There was a large overshoot in the horizontal displacement which damped very slowly and was followed by a high-frequency limit cycle. There is evidence in the single-loop tests that as the saturation limit is made more restrictive, K_2 increases and A decreases. (See table I.) Also there were times during a run at the lower control limits in which K_1 was reduced considerably (task 1: table I(a), fig. 4, and task 2: table I(b), fig. (11)). Since the multi-loop problem presents a situation where the saturation limit is many times more restrictive than in the most restricted case of the single-loop tests - requiring that the control remain on the limit for as long as 15 seconds during the first part of the run - it is evident that some extrapolation of the single-loop gains for use in this type of problem was required. Therefore, the K_1 gain of the outer loop was reduced to decrease the system frequency, and the K_2 gain was increased in order to increase the system damping.

By comparison with the gains shown in task 1, table I(g), it was observed that it was necessary to decrease the product K_1K by a factor of 64.5, to increase K_2 by a factor of 5, and to reduce A from 6 to 4. The gains for the inner-loop analog pilot were not altered.

These gain settings provided an overshoot in horizontal displacement that was very similar to that obtained in most of the piloted tests. (See fig. 19(b).) However, the characteristics of the time history in the linear portion of the control, that is, during the last part of the time history when the bank angle is always less than 30^o, were better than those which were obtained with the human pilot in control. In an attempt to obtain a closer reproduction of the linear portion of the maneuver, the values of A and K_2 obtained in the single-loop tests of task 1 (table I(g)) were used (that is, $A = 6$ and $K_2 = 6$) with the value of K_1K decreased by a factor of 10. (See fig. 19(c).)

It was shown in reference 4 that if a pilot has a two-axis task to perform in a fixed-base simulator, there are brief instances when the gain K_1 is greatly reduced or takes a value of zero. This effect is probably a result of a momentary diverting of attention from one of the axes. To simulate this factor in the present investigation, the K_1 gain of the inner-loop analog pilot was reduced to zero for short arbitrarily chosen times. The results are shown in figure 19(d). It can be seen that under this circumstance a randomly appearing variation in bank angle is produced which has a remarkable similarity to the linear portion of the time history obtained for the pilot. (See fig. 19(a).)

To illustrate the effect of the inner loop on the maneuver, the time history of the test has been repeated with the inner loop replaced with a transfer function of 1. As can be seen in figure 19(e), the effect of eliminating the inner loop is to increase the damping of the system.

This preliminary investigation illustrates that the measured values of K_2 and A obtained in simple single-axis single-loop tests can be applied to the more complicated multi-loop control situation where the control is linear. It also indicates the various changes in K_1, A, and K_2 that can be expected when the control is saturated for long periods of time.

CONCLUDING REMARKS

Tests have been performed using a single-degree-of-freedom manned control loop which included simulated nonlinear torque-producing elements. The nonlinearities included in these tests are torque limits and on-off control torques. Transfer functions of the pilot were obtained by matching an analog model with the pilot. This analog model contained a linear model in conjunction with a nonlinear element that was similar to the nonlinear control torque element. The good agreement between the time histories of the output of the pilot and that of the analog model and the close resemblance of the time histories of system output with the human pilot and the analog pilot in the loop demonstrate that this model can accurately represent the pilot. Additional confirmation of the validity of the model is supplied by the consistency of the measured gains in the model for similar control situations even though different matching signals were used.

The measurements made of the gains of the human pilots indicate that in general the pilots make only small changes in their control technique as the restrictions imposed by the nonlinearities are varied. There are a few instances which occurred in the tests that indicate a significant change in pilot-control technique when sufficient restriction was imposed.

The model forms used to represent the human pilot in these single-loop tests were applied to a multi-loop control problem, and the result demonstrates that the use of such models is feasible in the multi-loop case.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 24, 1964.

REFERENCES

1. Adams, James J.: A Simplified Method for Measuring Human Transfer Functions. NASA TN D-1782, 1963.

2. Adams, James J.; and Bergeron, Hugh P.: Measured Variation in the Transfer Function of a Human Pilot in Single-Axis Tasks. NASA TN D-1952, 1963.

3. Adams, James J.; and Bergeron, Hugh P.: Measurements of Human Transfer Function with Various Model Forms. NASA TN D-2394, 1964.

4. Bergeron, Hugh P.; and Adams, James J.: Measured Transfer Functions of Pilots During Two-Axis Tasks with Motion. NASA TN D-2177, 1964.

5. Goode, Maxwell W.: Visual Simulation Study of Lunar Hovering, Translation, and Touchdown. A Compilation of Recent Research Related to the Apollo Mission. NASA TM X-890, 1963, pp. 27-35.

TABLE I.- SUMMARY OF DATA

(a) Pilot B: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains K_1	Measured gains A, radians/sec	Measured gains K_2	Closed-loop characteristics, Oscillatory ω_n, radians/sec	Closed-loop characteristics, Oscillatory ζ	Closed-loop characteristics, Real roots	Root-mean-square error, volts
10	9	11.5	3.5	3.18	0.142	-6.56, -15.5	2.71
5	8.5	9.5	4	3.93	.161	-3.72, -14.0	2.28
3	10	10	5	4.81	.193	-2.82, -15.3	2.41
2	11	7.5	4.5	5.74	.009	-1.90, -13.2	2.45
1	8.5	7.5	7.5	6.51	.006	-1.07, -14.0	3.74
1	4.5	5.5	7.5	5.43	.060	-0.77, -10.8	

(a) Continued. Pilot B: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains K_1	Measured gains A, radians/sec	Measured gains K_2	Closed-loop characteristics, Oscillatory ω_n, radians/sec	Closed-loop characteristics, Oscillatory ζ	Closed-loop characteristics, Real roots	Root-mean-square error, volts
5	8.5	12	4.5	3.20	0.238	-6.06, -16.4	2.95
3	7.5	8	3	3.65	.050	-3.80, -11.8	2.29
2	8.5	7.5	5	5.34	.039	-1.74, -12.8	2.65
1	7	10	5	3.73	.266	-3.46, -14.6	4.39

(a) Concluded. Pilot B: task 3; on-off torque

Step voltage, volts	Measured gains K_1	Measured gains A, radians/sec	Measured gains K_2	$\frac{2.5}{K_1/A}$, volts	Root-mean-square error, volts
5	20	20	4	2.5	2.38
3	20	10	4	1.25	2.47
*3	18	17	5	2.64	1.49
*2	16	15	5	2.34	1.20
*1	17	11	6	1.62	1.30

*Disturbance amplitude reduced 1/2.

TABLE I.- SUMMARY OF DATA - Continued

(b) Pilot D: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
10	8	11	5	3.63	0.283	-4.26, -15.7	2.00
5	7.5	10	4	3.41	.187	-4.55, -14.2	2.21
3	6.5	12	5	2.76	.272	-6.36, -16.1	2.21
2	8.5	10	5.5	4.64	.236	-2.59, -15.2	2.32
1	8	10	8	5.75	.211	-1.51, -16.1	3.6

(b) Continued. Pilot D: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
5	7	10	3.5	3.08	0.141	-5.38, -13.8	2.19
3	7	10	4	3.25	.190	-4.72, -14.0	2.26
2	5	11	7	3.14	.461	-3.60, -15.5	3.27
1	7.5	10.5	5.5	3.97	.301	-3.26, -15.4	4.28
1	2.5	14	6.5	1.41	.218	-10.5, -16.9	

(b) Concluded. Pilot D: task 3; on-off torque

Step voltage, volts	Measured gains			$\frac{2.5}{K_1/A}$, volts	Root-mean-square error, volts
	K_1	A, radians sec	K_2		
5	10	15	7	3.75	2.49
3	8.5	11	6	3.24	2.19
2	9	10	7	2.78	2.28
1	7	10	5	3.57	3.87

TABLE I.- SUMMARY OF DATA - Continued

(c) Pilot J: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
10	6.5	11	5	3.07	0.288	-4.96, -15.3	2.00
5	5	11	4.5	2.44	.223	-6.33, -14.6	2.33
3	5	11	5	2.52	.272	-5.83, -14.8	2.07
2	4.5	12	5	2.16	.236	-7.48, -15.5	2.41
1	7	10.5	6.5	4.34	.333	-2.49, -15.6	3.31
.5	9.5	10	6.5	5.57	.193	-1.92, -15.9	5.00

(c) Continued: Pilot J: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
5	5	10.5	5	2.67	0.282	-5.10, -14.4	2.50
3	4.5	12	5.5	2.20	.278	-7.09, -15.7	2.30
2	5	12	5	2.31	.247	-7.19, -15.7	2.55
1	6	22	5.5	1.69	.132	-18.4, -25.2	2.51

(c) Concluded. Pilot J: task 3; on-off torque

Step voltage, volts	Measured gains			$\frac{2.5}{K_1/A}$, volts	Root-mean-square error, volts
	K_1	A, radians/sec	K_2		
5	16	24	8	3.75	2.91
3	16	22	9	3.44	2.45
2	15	20	9	3.33	2.55
1	16	20	10	3.12	4.45

TABLE I.- SUMMARY OF DATA - Continued

(d) Pilot K: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
10	5	12	5.5	2.37	0.292	-6.75, -15.9	2.19
5	4	12	5	2.01	.224	-7.78, -15.3	3.04
3	6	11	5.5	3.04	.334	-4.64, -15.3	2.18
2	6	11.5	6	3.01	.375	-4.76, -15.3	2.30
1	5	12	6	2.43	.340	-6.30, -16.0	3.40

(d) Continued. Pilot K: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics			Root-mean-square error, volts
				Oscillatory		Real roots	
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ		
5	5	12	5.5	2.37	0.292	-6.75, -16.0	2.26
3	5.5	14	6	2.21	.286	-8.74, -18.0	2.68
2	4.5	14	5	1.91	.190	-9.97, -17.3	2.51
1	4	14	5	1.79	.180	-10.2, -17.1	2.81

(d) Concluded. Pilot K: task 3; on-off torque

Step voltage, volts	Measured gains			$\frac{2.5}{K_1/A}$, volts	Root-mean-square error, volts
	K_1	A, radians/sec	K_2		
5	8	13	4.5	4.06	2.32
3	8	11	5	3.44	2.32
2	9.5	9	6	2.37	2.04
1	8	11	8	3.44	3.61

TABLE I.- SUMMARY OF DATA - Continued

(e) Pilot L: task 1; linear stick; limited torque

Cut-off voltage, volts (*)	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
10	5	8	2.5	2.72	0.028	-5.0, -10.9
5	6.5	10.5	2.5	2.62	.036	-7.39, -13.4
3	8	10	3	3.18	.086	-5.80, -13.6
2	8	9.5	2.5	3.15	.028	-5.97, -12.8

*Disturbance break-point frequency = 0.06 radian/sec.

(e) Continued. Pilot L: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
5	7	11	2.5	2.65	0.038	-7.87, -13.9
3	8	10	3	3.18	.086	-5.80, -13.6
1	5.5	11	2	2.28	.008	-8.83, -13.2

(e) Concluded. Pilot L: task 3; on-off torque

Step voltage, volts (*)	Measured gains			$\frac{2.5}{K_1/A}$, volts
	K_1	A, radians/sec	K_2	
5	8	8	3	2.50
3	6.5	6.5	3	2.50
1	5.5	6.5	4	2.95

*Disturbance break-point frequency = 0.06 radian/sec.

TABLE I.- SUMMARY OF DATA - Continued

(f) Pilot A: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
10	7.5	7.5	6	5.51	0.045	-1.41, -13.1
5	8.5	7.5	7	6.30	.003	-1.16, -13.8
3	7	6	6.5	6.00	.076	-0.98, -11.9

(f) Continued. Pilot A: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
5	10.5	7	7	7.06	0.074	-1.05, -14.0
**,*5	6	11	8.5	6.97	.165	-1.49, -18.2
**,*3	7	9.5	7.5	7.50	.037	-1.39, -17.1
**,*1	5.5	8.5	6.5	6.52	.035	-1.46, -15.1

*Disturbance break-point frequency = 0.06 radian/sec.
**Vehicle dynamics = $20/s^2$.

(f) Concluded. Pilot A: task 3; on-off torque

Step voltage, volts (*)	Measured gains			$\frac{2.5}{K_1/A}$, volts
	K_1	A, radians/sec	K_2	
5	9.5	10	7.5	2.63
3	11.5	8.5	9.0	1.85
1	11.5	5.5	5.5	1.20

*Disturbance break-point frequency = 0.06 radian/sec.

TABLE I.- SUMMARY OF DATA - Continued

(g) Engineer G: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
5	8	7.5	5	5.18	0.049	-1.76, -12.7
3	11	6	5	6.50	.124	-1.27, -12.3
2	8.5	5	5	6.11	.162	-1.04, -10.9
1	6.5	6	6	5.61	.056	-1.07, -11.6

(g) Continued. Engineer G: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		Real roots
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	
3	5.5	7.5	5.5	4.47	0.129	-1.69, -12.2
1	2.5	7	5	2.70	.259	-2.36, -10.2

(g) Concluded. Engineer G: task 3; on-off torque

Step voltage, volts	Measured gains			$\frac{2.5}{K_1/A}$, volts
	K_1	A, radians/sec	K_2	
5	5	5	3.5	2.50
3	5	5	5	2.50
2.5	6.25	5.5	5	2.20

TABLE I.- SUMMARY OF DATA - Concluded

(h) Engineer H: task 1; linear stick; limited torque

Cut-off voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	Real roots
10	8	9.5	5	4.37	0.207	-2.76, -14.4
5	10	10	6	5.44	.187	-2.14, -15.8
3	11	7.5	5	6.04	.017	-1.67, -13.5
1	11	9.5	7.5	6.71	.091	-1.42, -16.4

(h) Continued. Engineer H: task 2; limited stick; limited torque

Limit voltage, volts	Measured gains			Closed-loop characteristics		
				Oscillatory		
	K_1	A, radians/sec	K_2	ω_n, radians/sec	ζ	Real roots
5	8	10	7	5.28	0.235	-1.83, -15.7
3	8.5	8	5	5.16	.075	-1.92, -13.3
1	9	8	4	4.70	.064	-2.53, -12.9

(h) Concluded. Engineer H: task 3; on-off torque

Step voltage, volts	Measured gains			$\frac{2.5}{K_1/A}$, volts
	K_1	A, radians/sec	K_2	
5	9	10.5	5	2.92
3	9.5	9.5	4.5	2.50
1	9.5	8	5.5	2.11

TABLE II.- ROOT-MEAN-SQUARE ERROR WITH HUMAN PILOT

AND ANALOG PILOT IN THE LOOP

Task	Maximum voltage limit, volts	Disturbance break-point frequency, radians/sec	Pilot root-mean-square error, volts	Analog pilot root-mean-square error, volts
Pilot A				
1	3	0.125	2.67	1.85
1	3	.06	.837	.670
1	1	.06	.912	.817
2	3	.06	1.15	.6
3	3	.06	.812	.633
3	1	.06	1.52	1.10
Pilot B				
1	3	0.125	1.76	1.41
2	3	.125	3.02	2.53
2	2	.06	.913	.954
2	1	.06	1.38	1.95
3	---	-----	-----	-----
Pilot L				
1	2	0.125	3.81	2.40
1	2	.06	1.32	1.51
2	3	.125	2.03	2.00
3	3	.06	1.94	1.94
3	1	.06	2.14	2.07

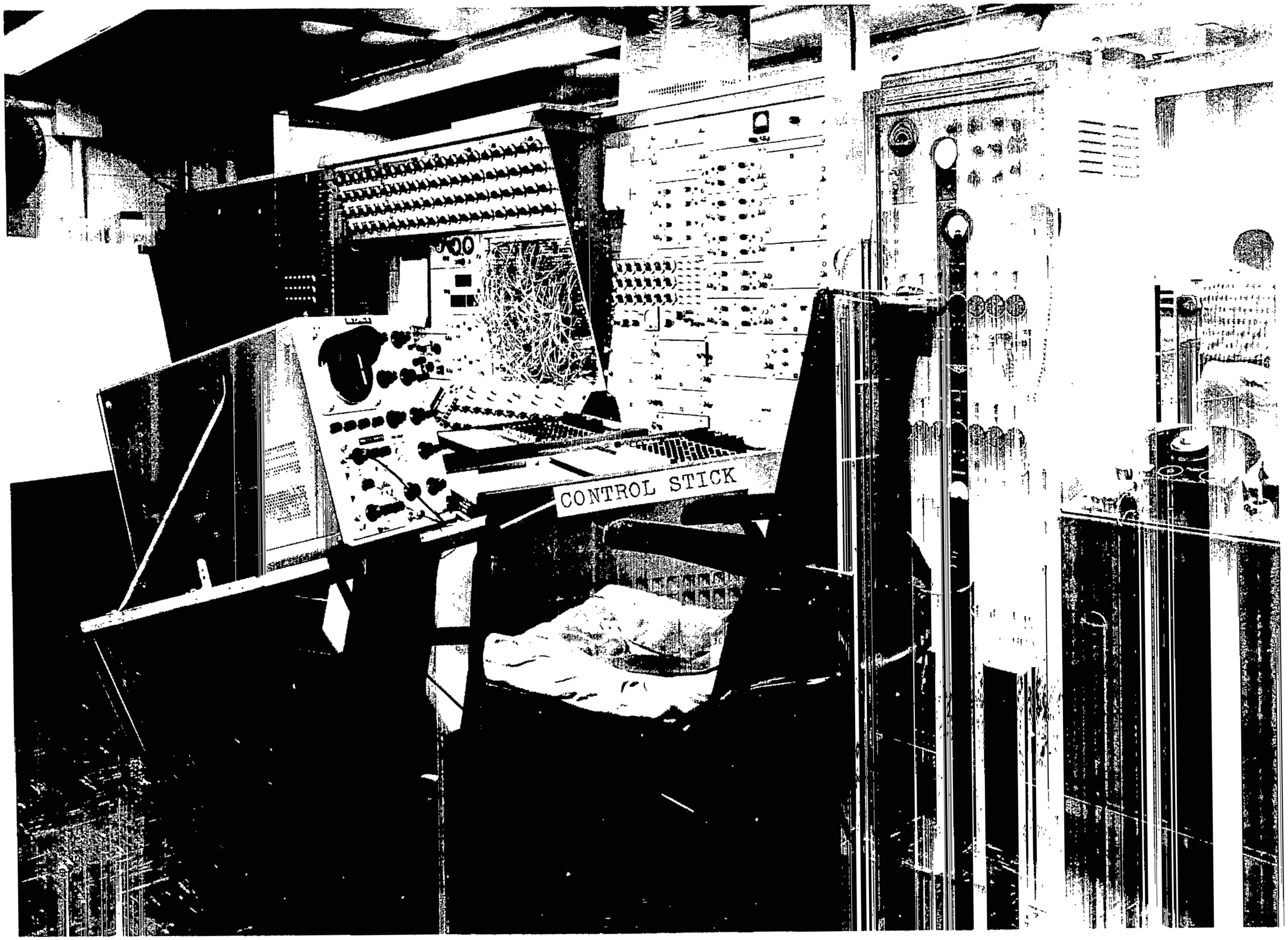


Figure 1.- Photograph of simulator and computer used in tests.

L-62-7541.1

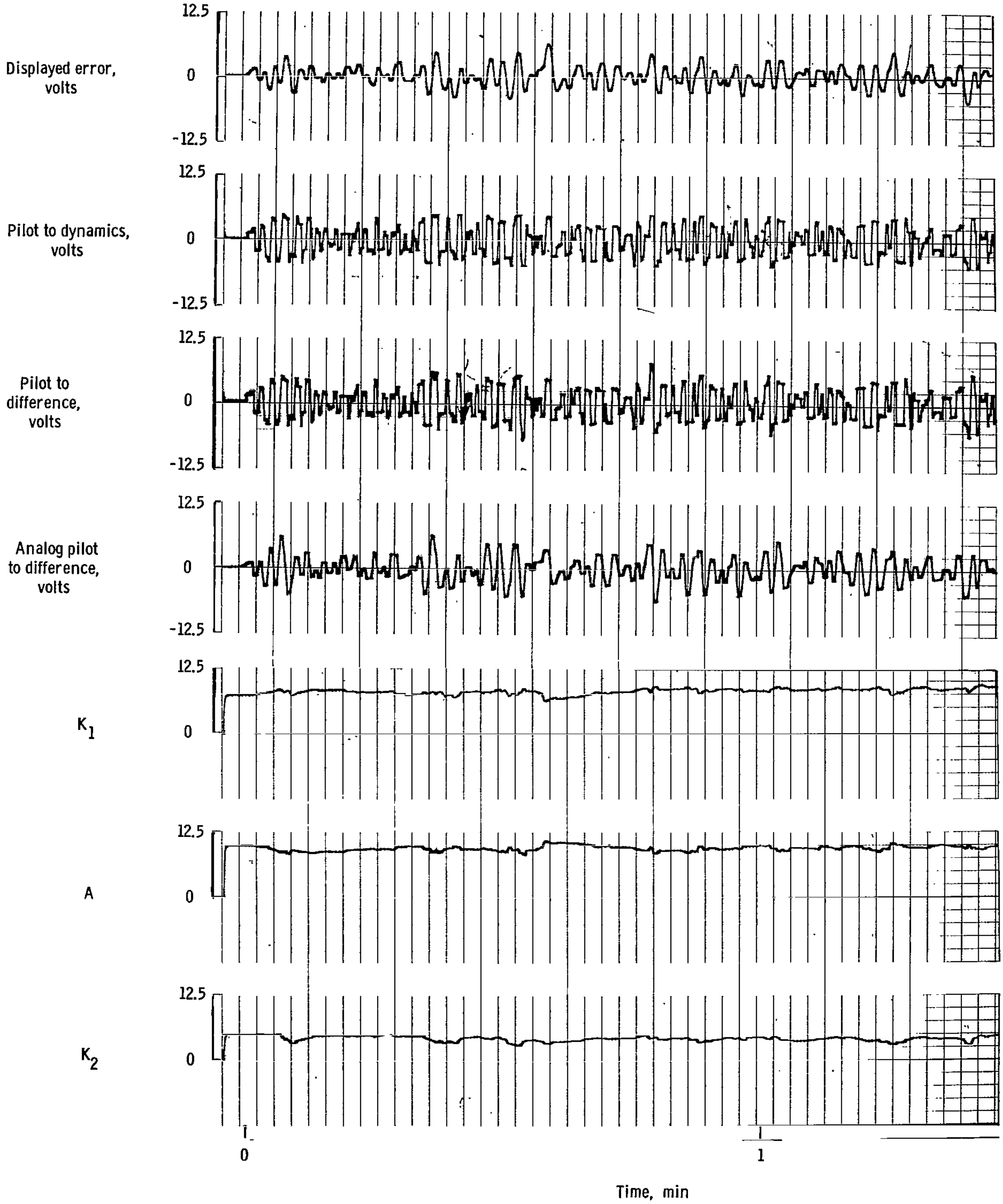


Figure 2.- Pilot B performing task 1 (linear stick with limited voltage output of ±5 volts).

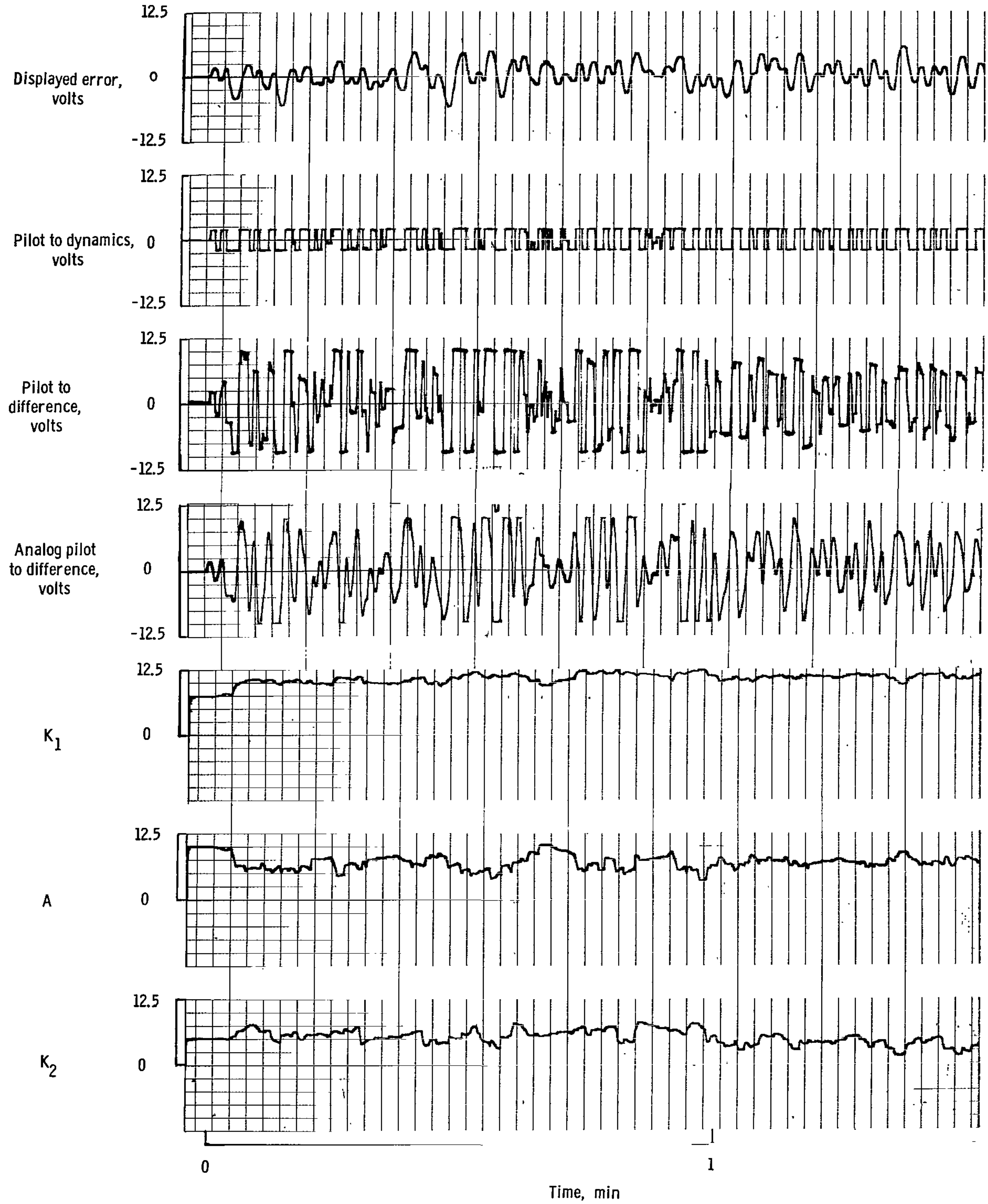


Figure 3.- Pilot B performing task 1 (linear stick with limited voltage output of ±2 volts).

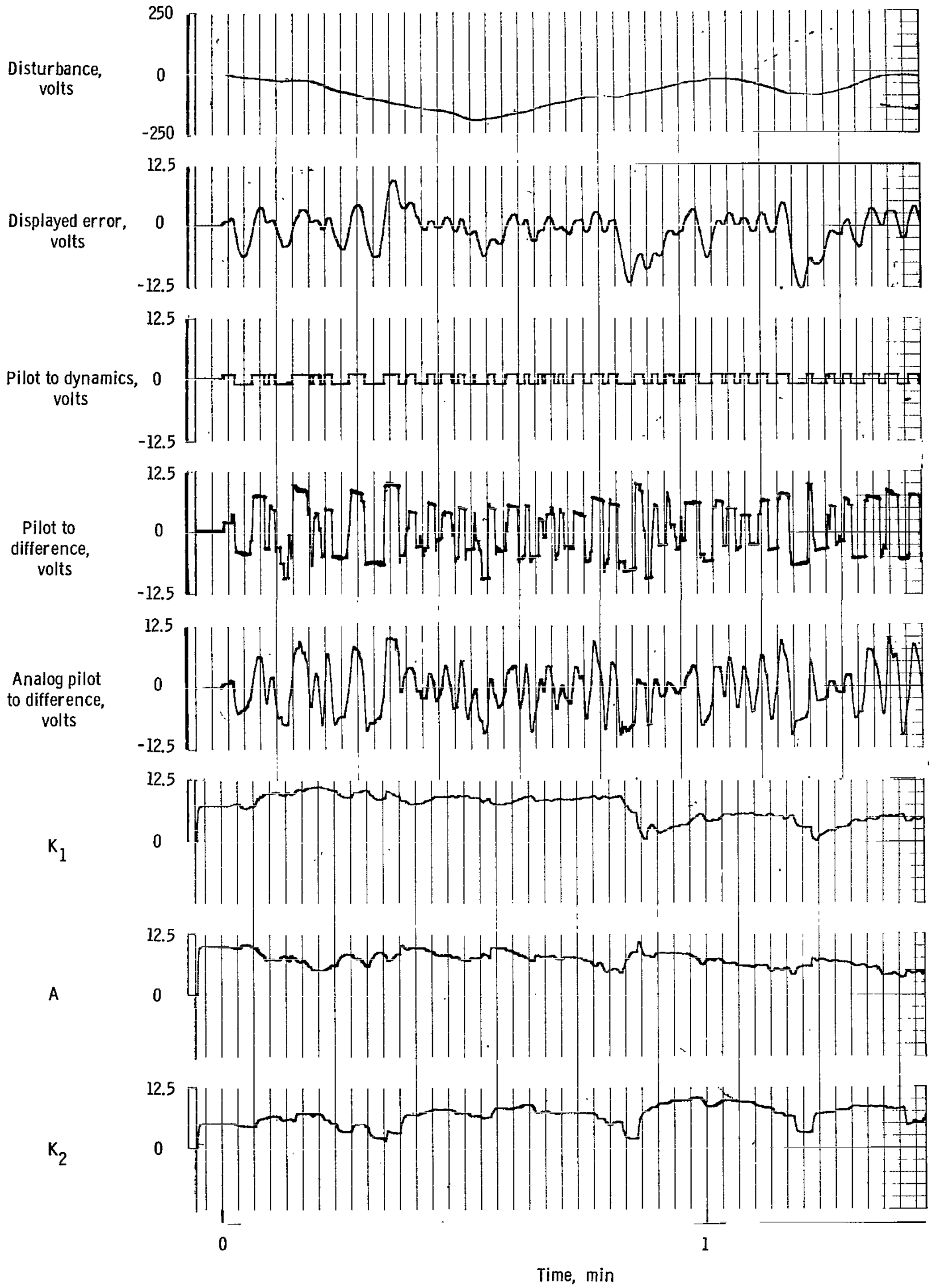


Figure 4.- Pilot B performing task 1 (linear stick with limited voltage output of ±1 volt).

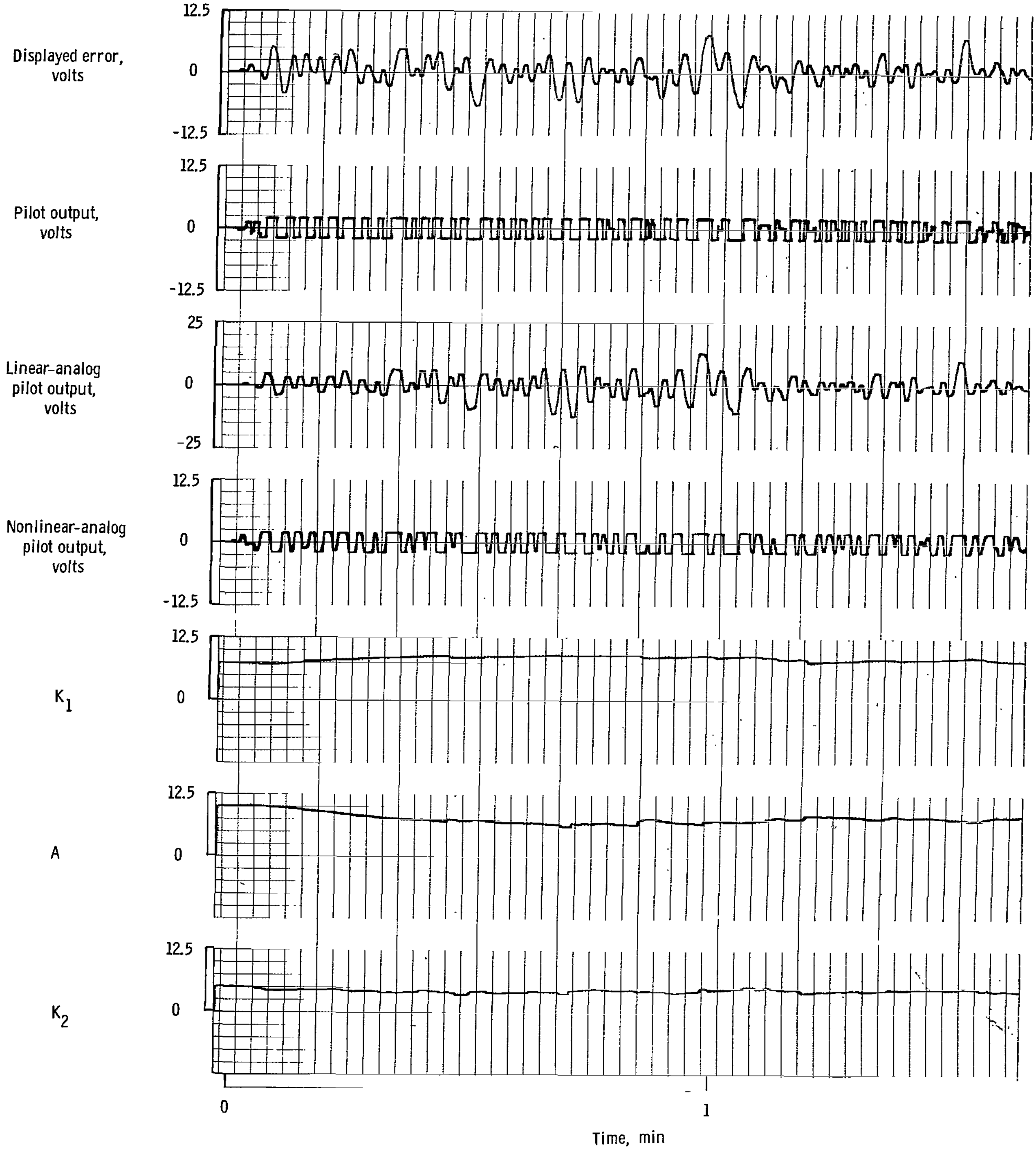


Figure 5.- Pilot B performing task 2 (limited stick and voltage output of ±2 volts).

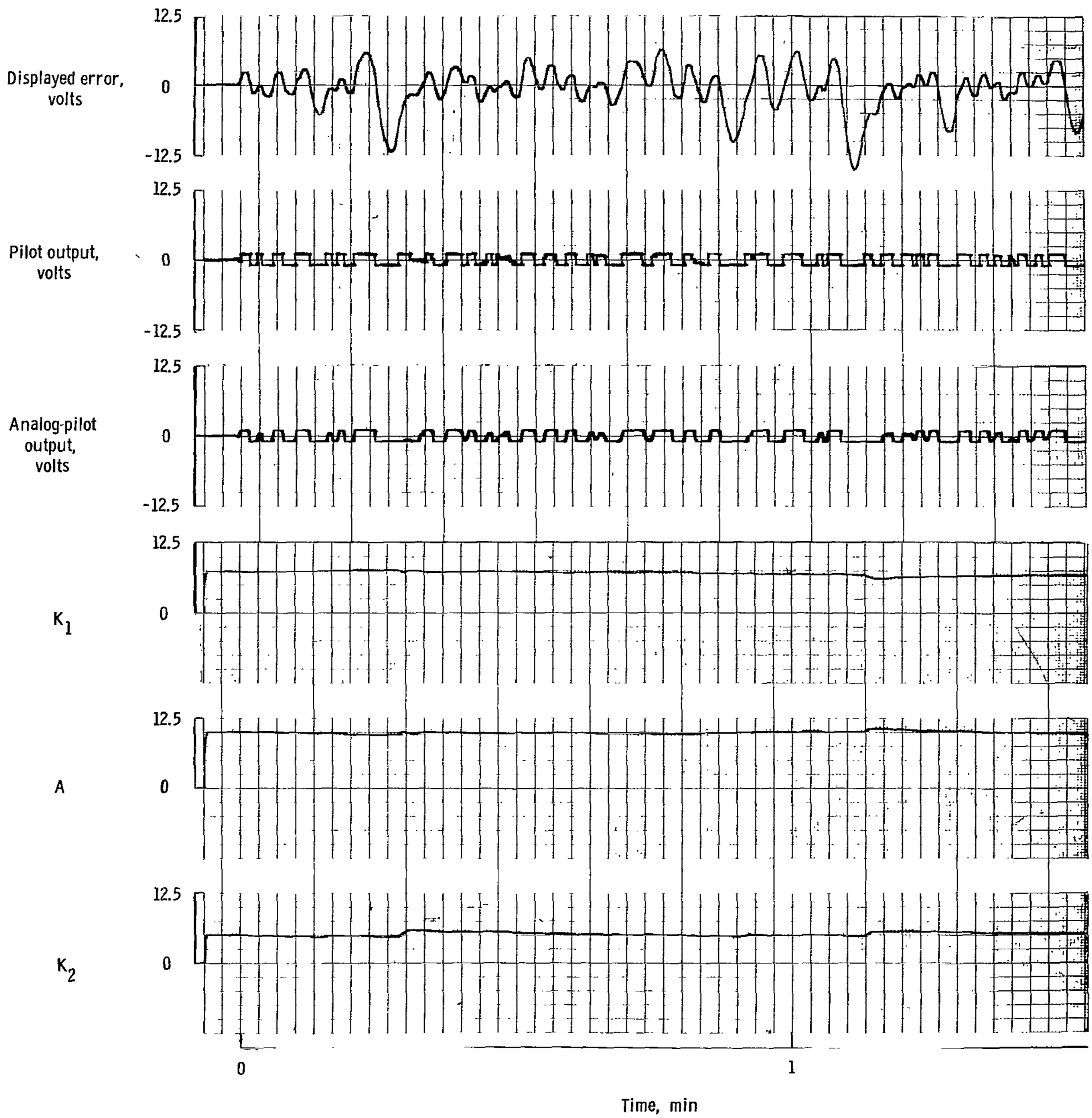


Figure 6.- Pilot B performing task 2 (limited stick and voltage output of ±1 volt).

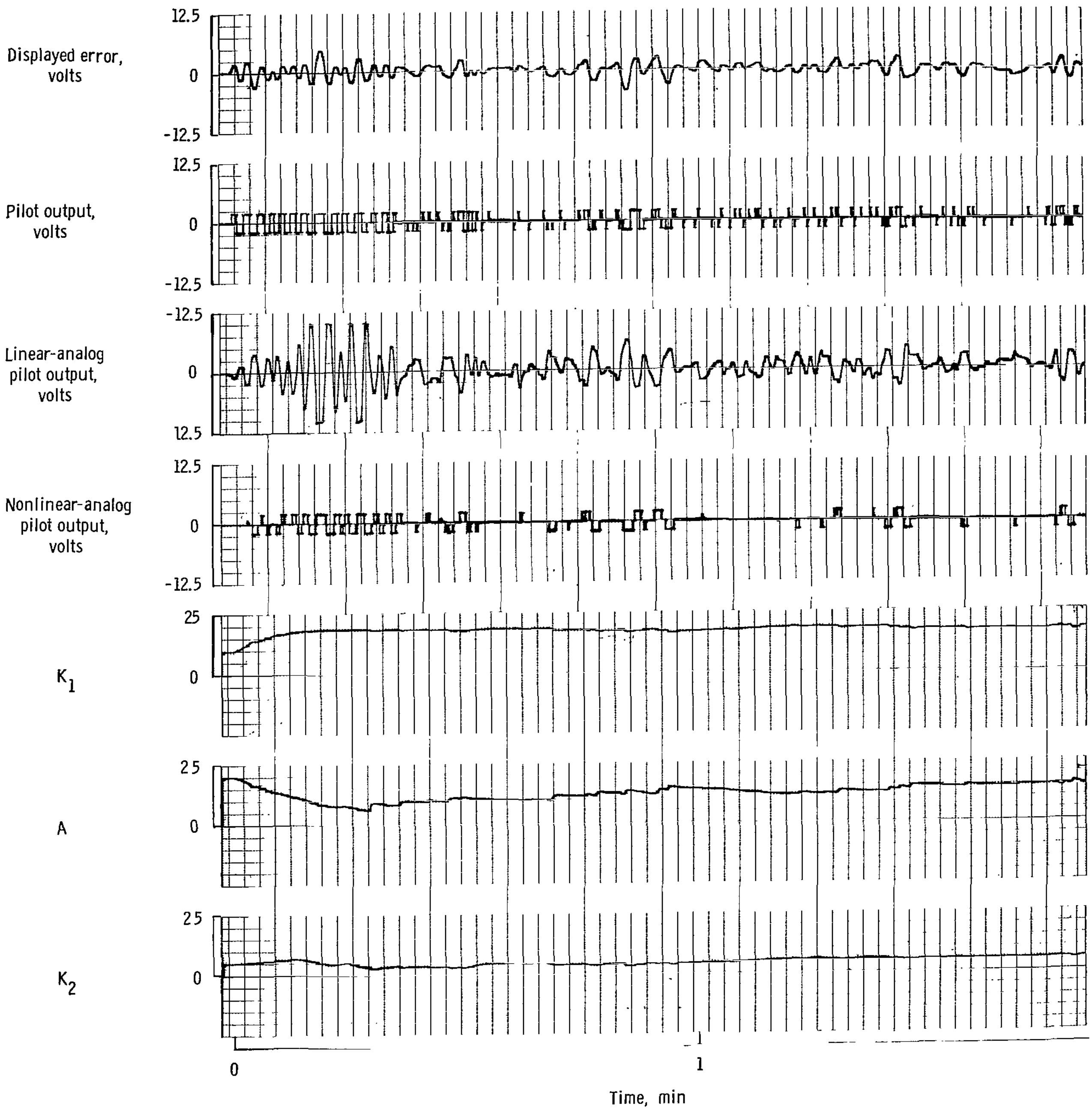


Figure 7.- Pilot B performing task 3 (on-off voltage output of ±2 volts).

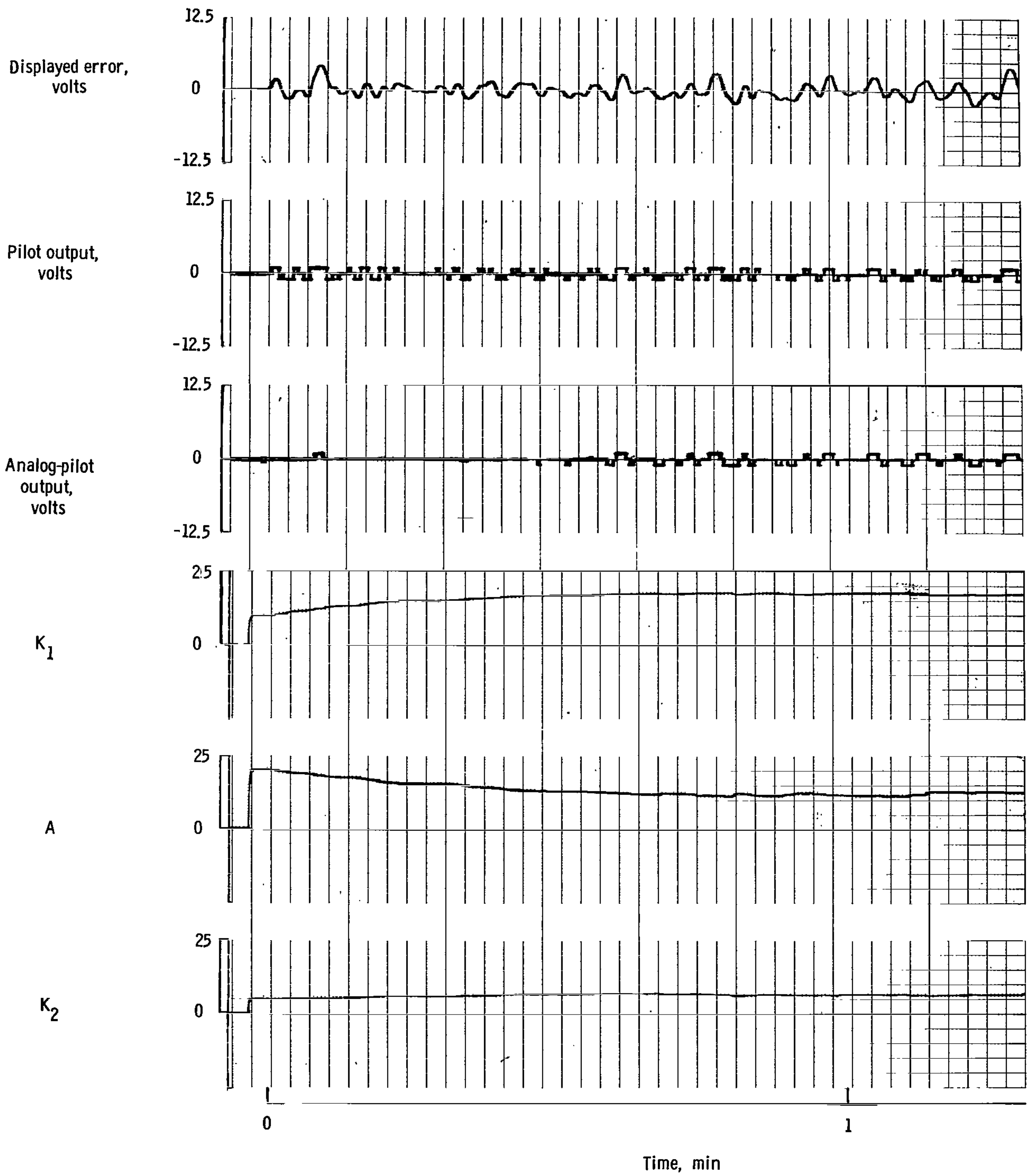


Figure 8.- Pilot B performing task 3 (on-off voltage output of ±1 volt).

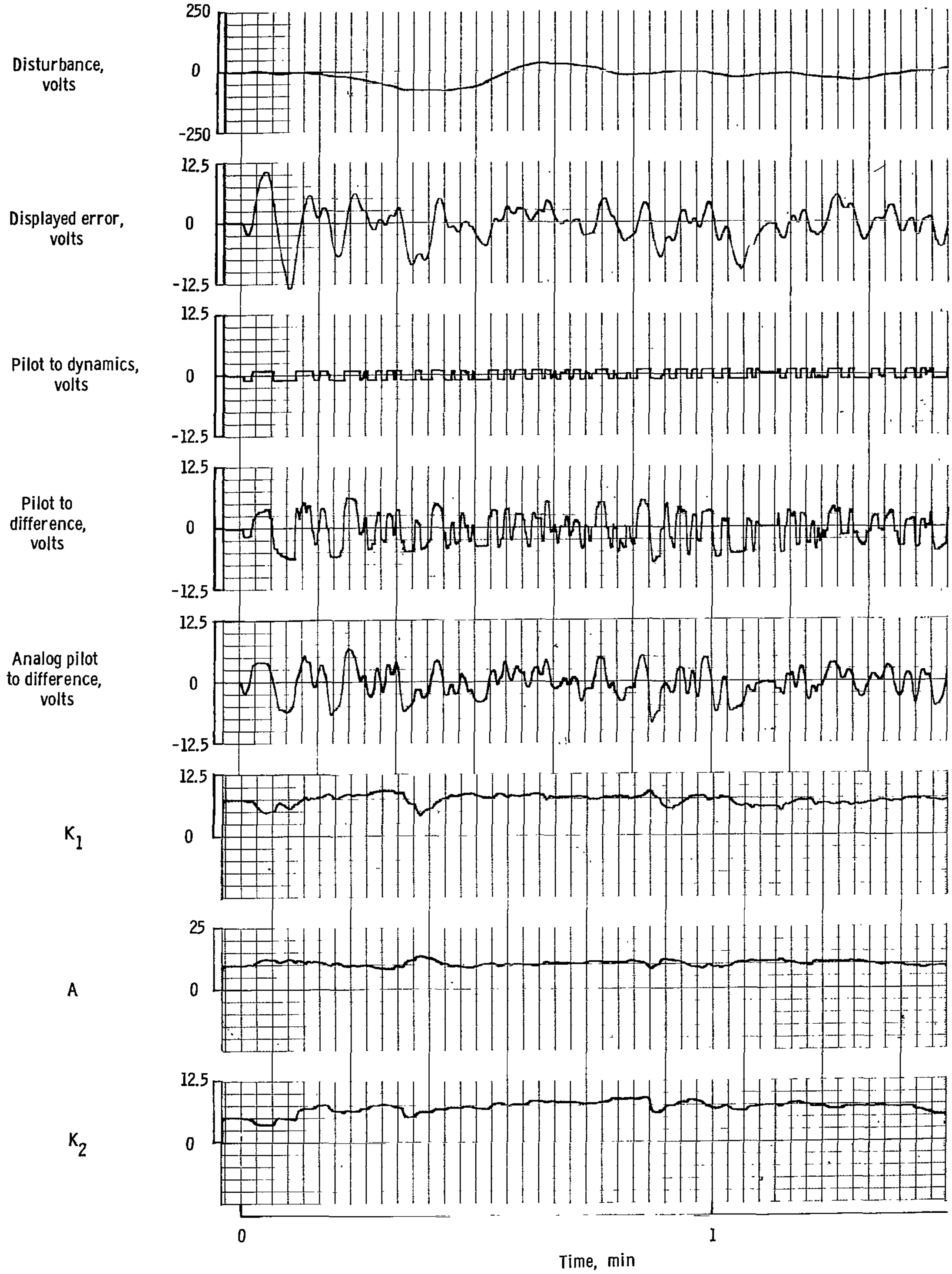


Figure 9.- Pilot D performing task 1 (linear stick with limited voltage output of ±1 volt).

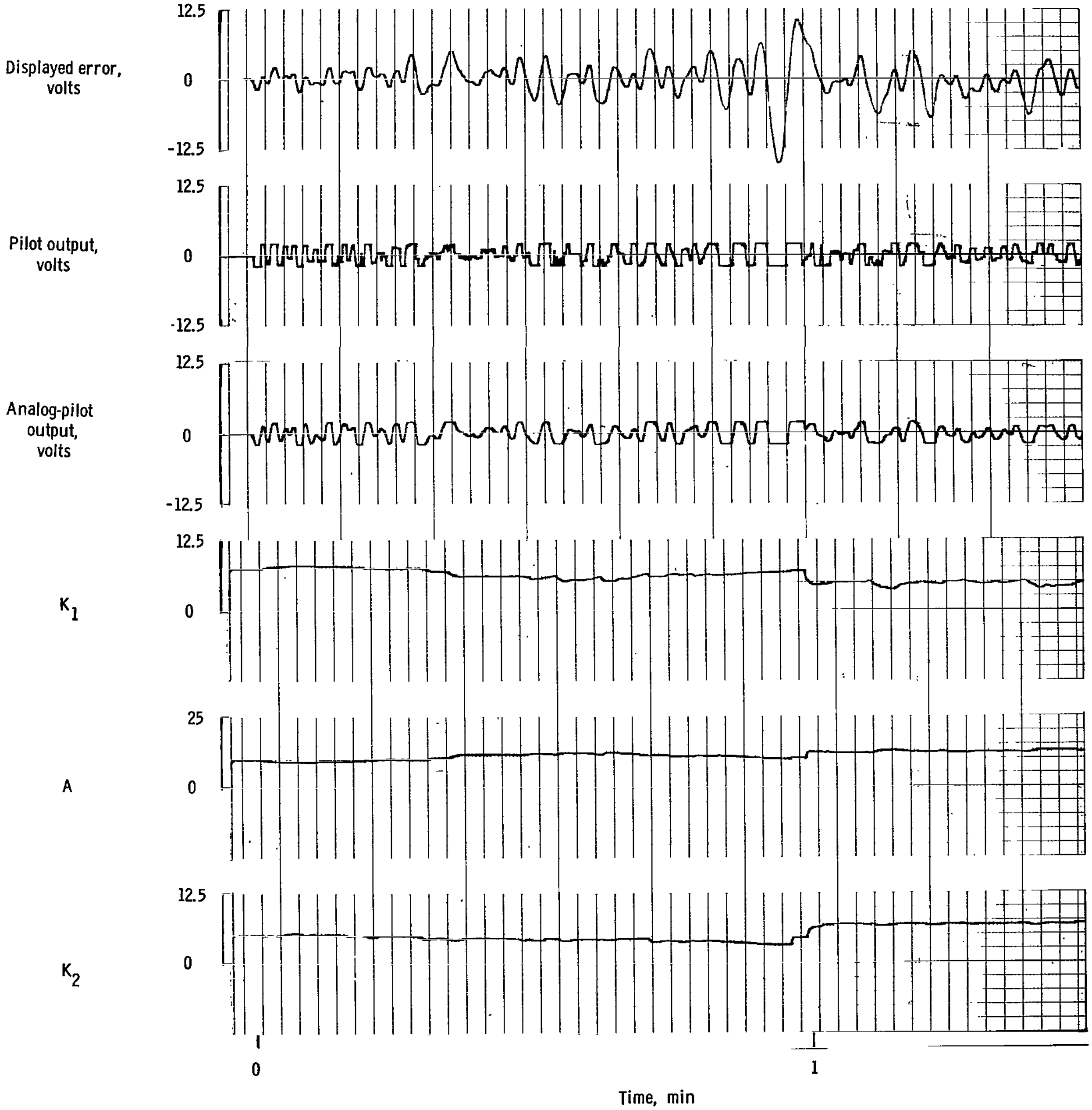


Figure 10.- Pilot D performing task 2 (limited stick and voltage output of ±2 volts).

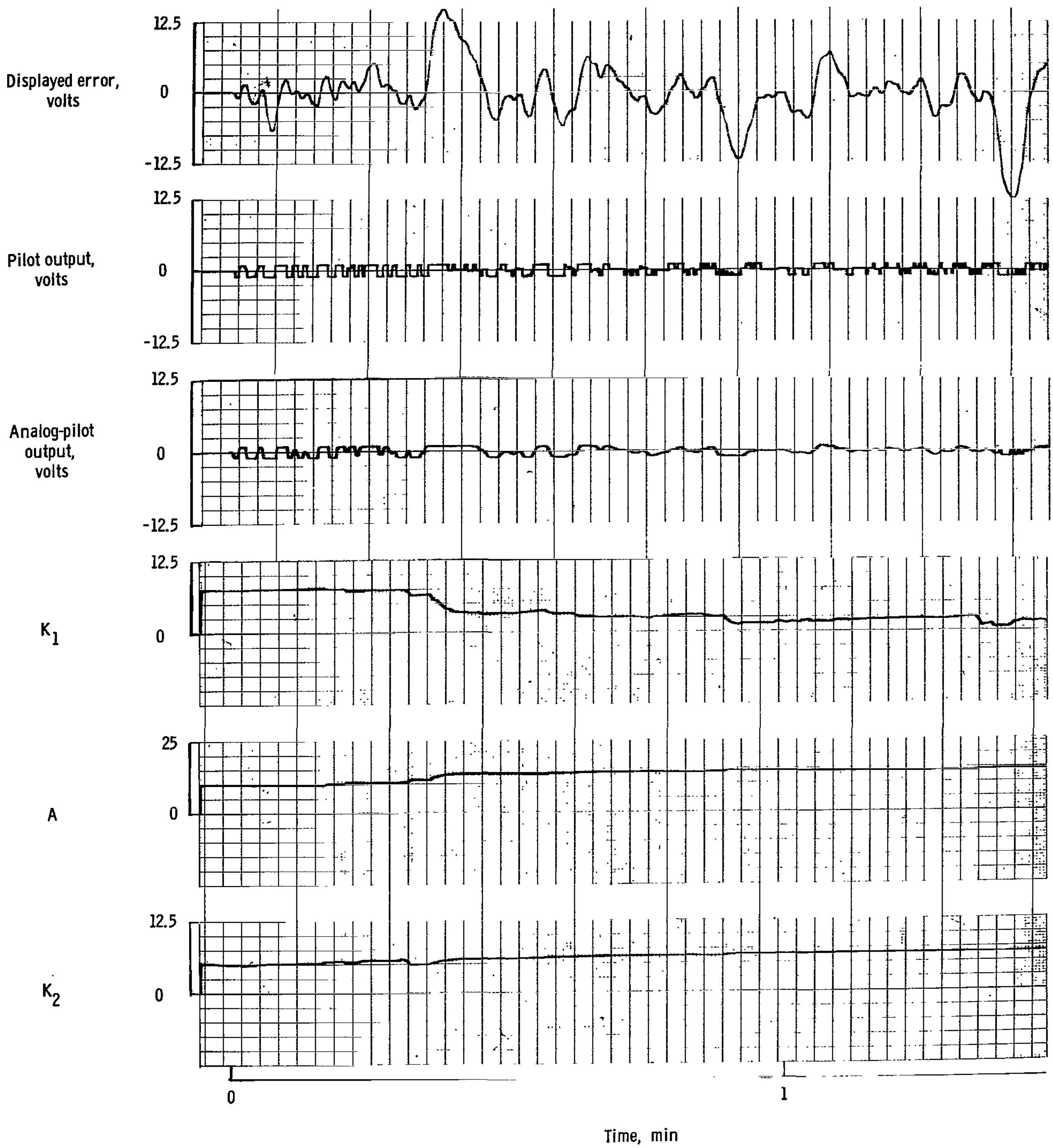


Figure 11.- Pilot D performing task 2 (limited stick and voltage output of ±1 volt).

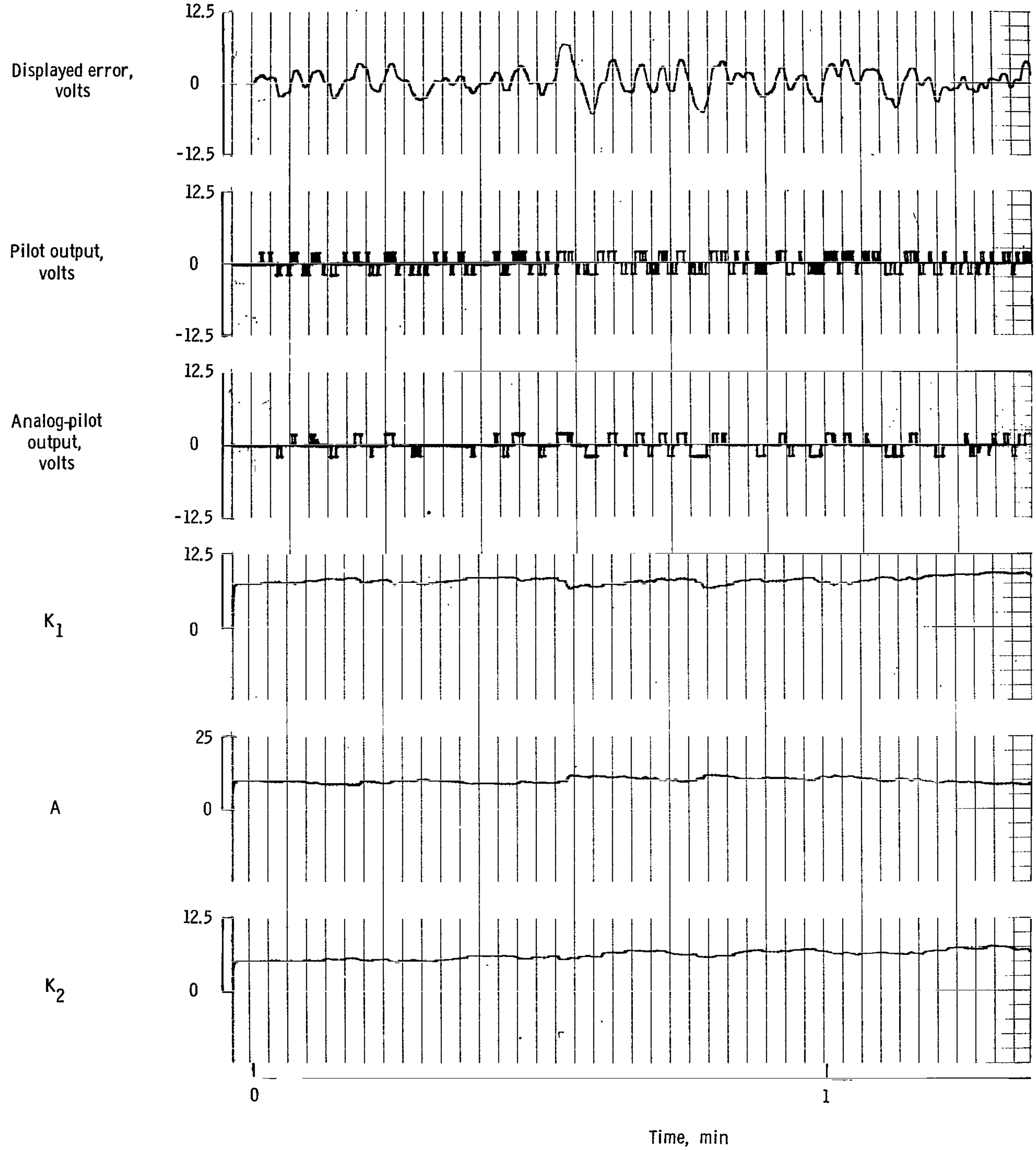


Figure 12.- Pilot D performing task 3 (on-off voltage output of ±2 volts).

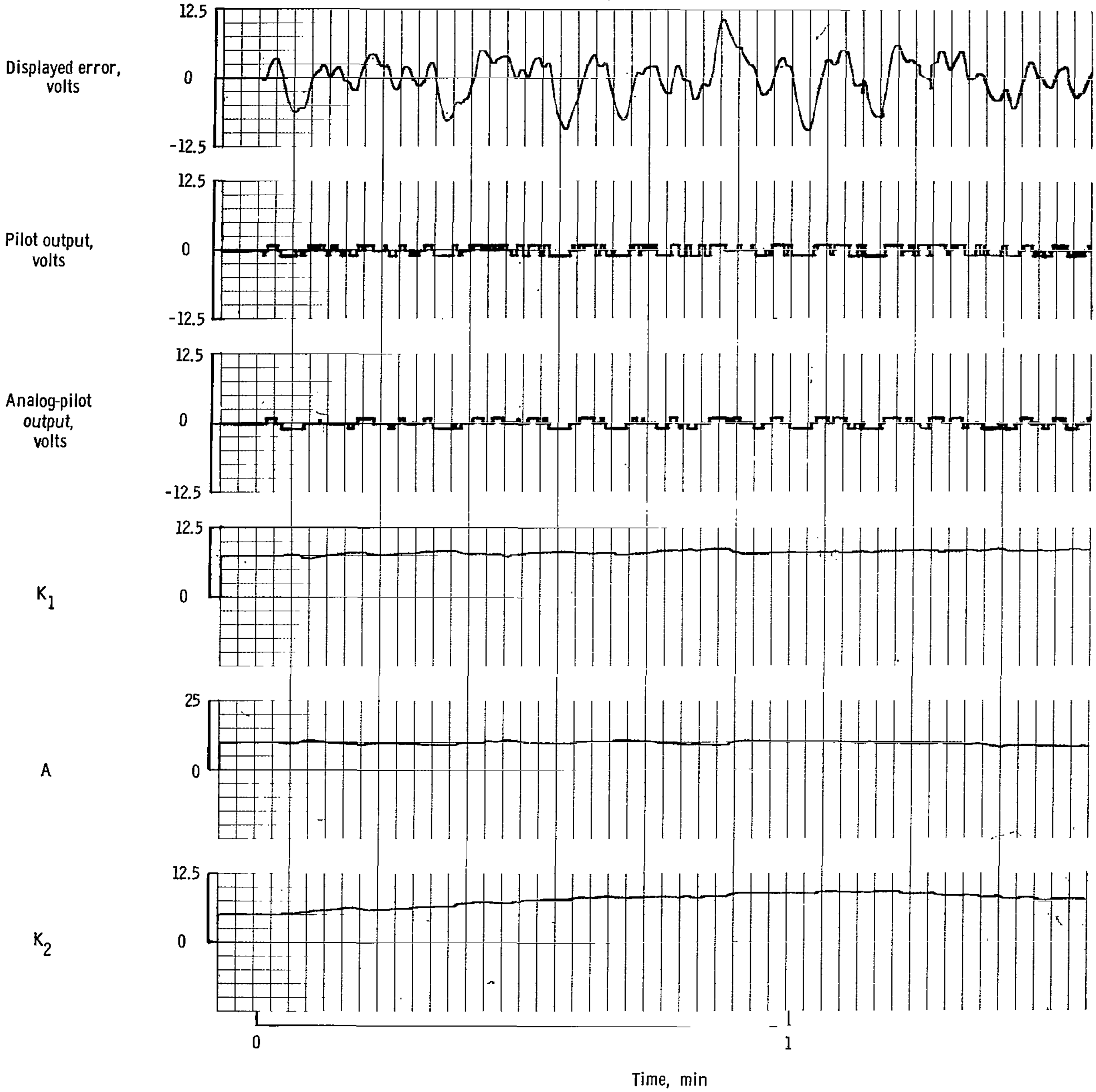


Figure 13.- Pilot D performing task 3 (on-off voltage output of ±1 volt).

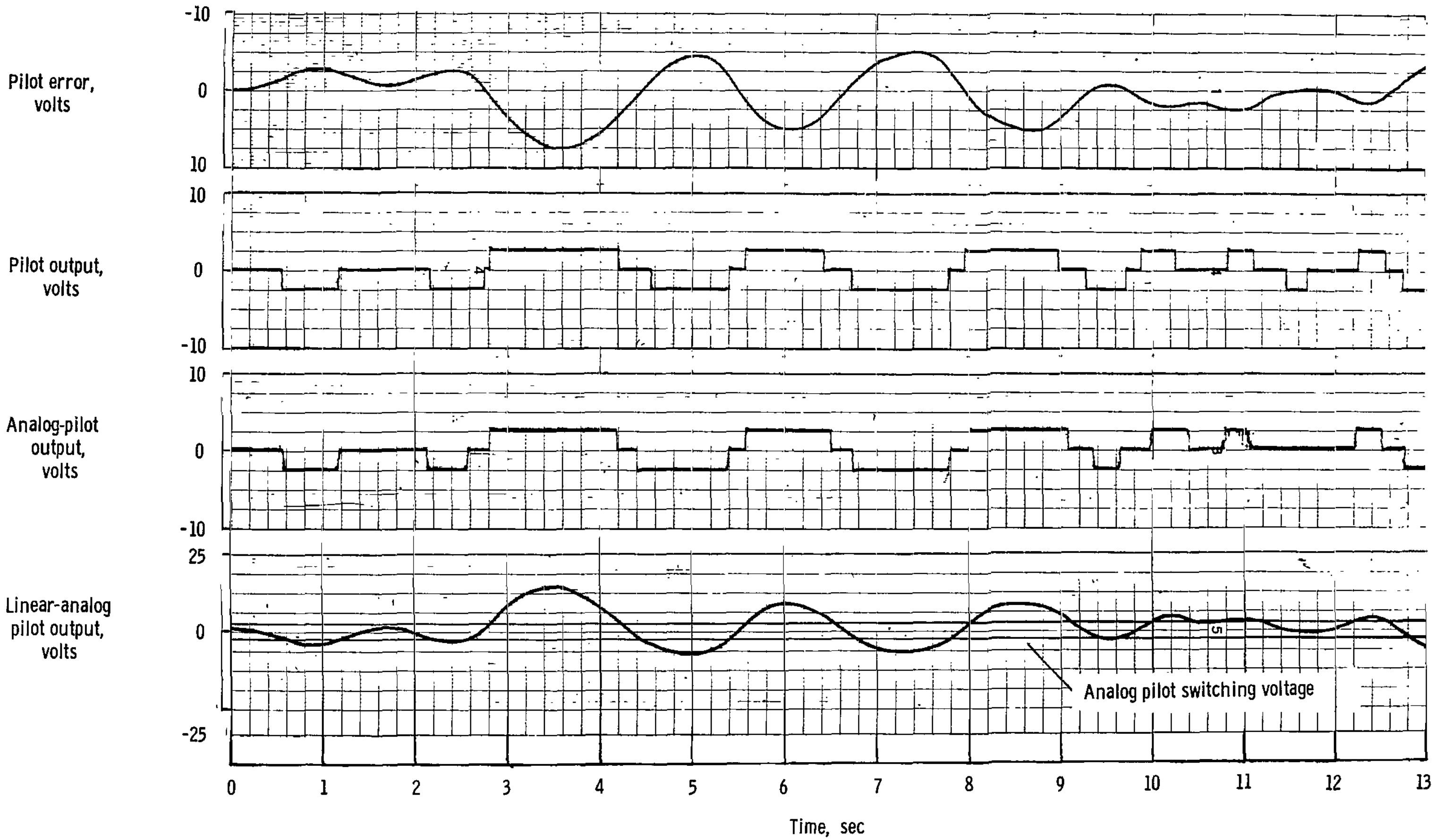


Figure 14.- Engineer G, expanded time scale of task 3 with ±2.5-volt step. Zero does not indicate beginning of run.

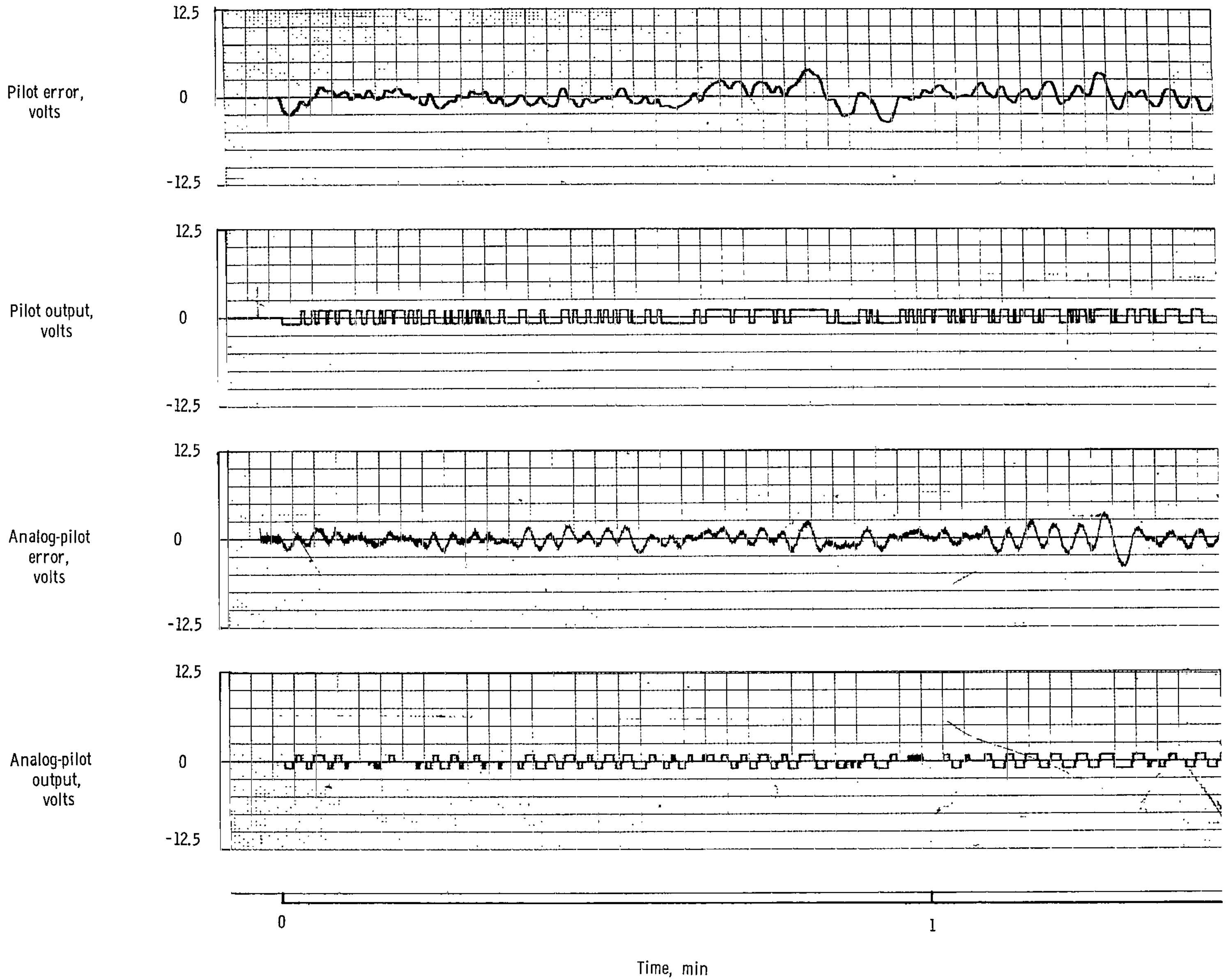


Figure 15.- Comparison of human pilot and analog pilot in loop with gains for analog pilot taken from table I(f), task 3.

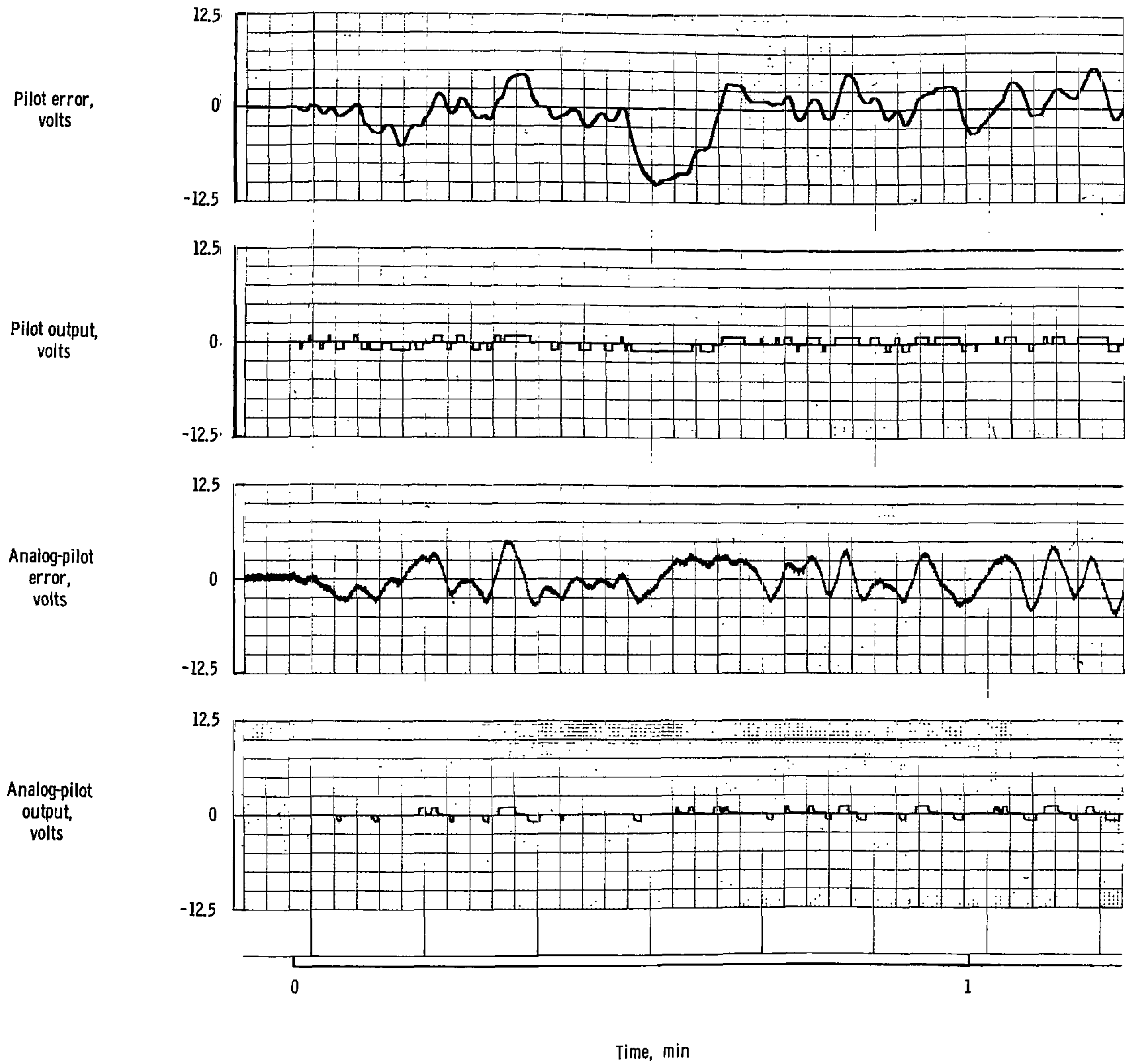
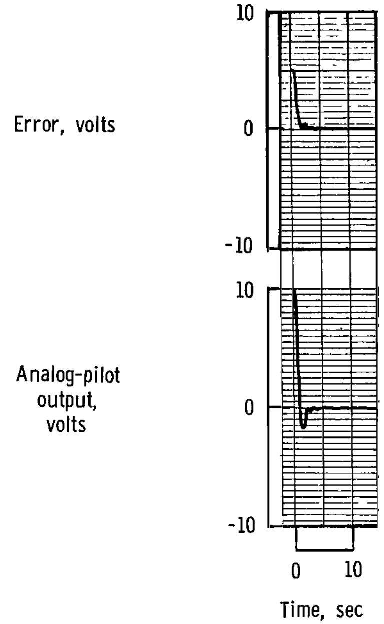
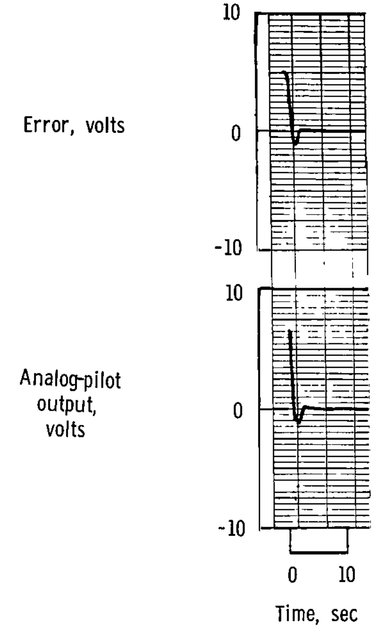


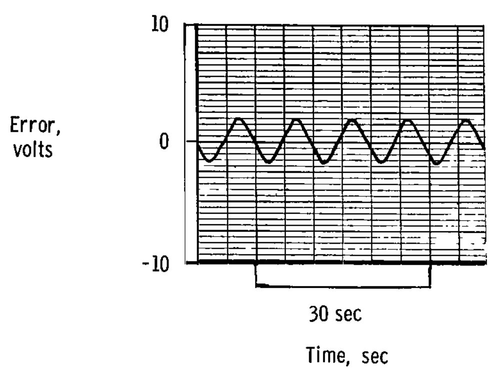
Figure 16.- Comparison of human pilot and analog pilot in loop with gains for analog pilot taken from table I(e), task 3.



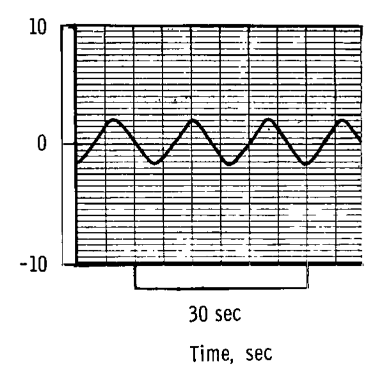
(a) ±1 volt-limit; task 1.



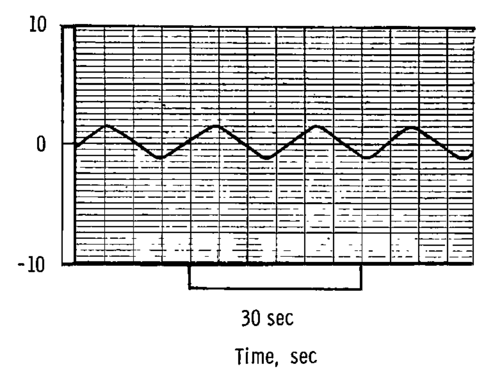
(b) ±1-volt limit; task 2.



(c) Torque level, ±3 volts, task 3.

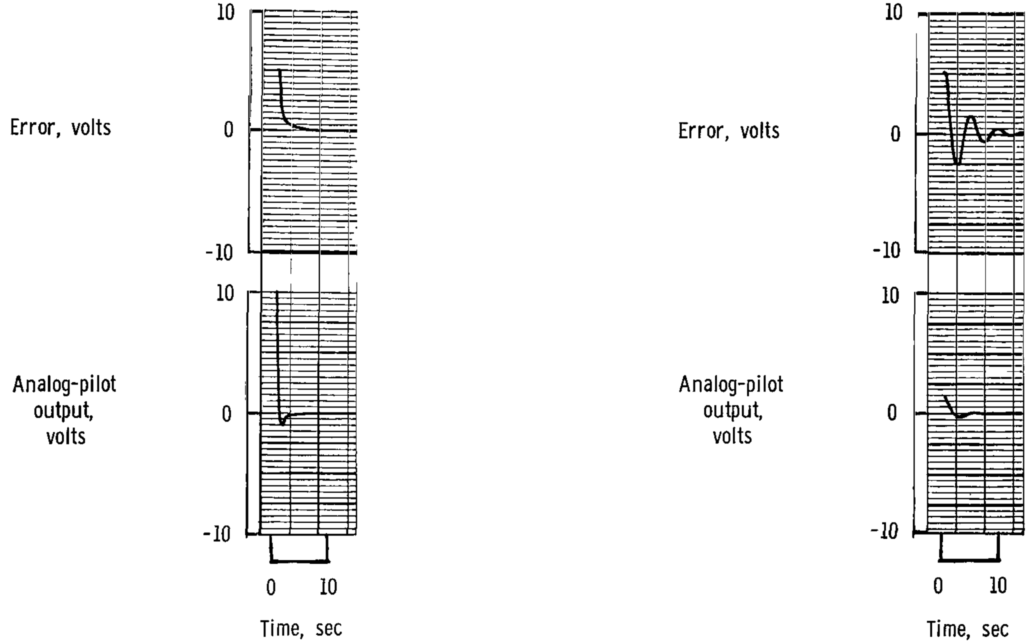


(d) Torque level, ±2 volts, task 3.



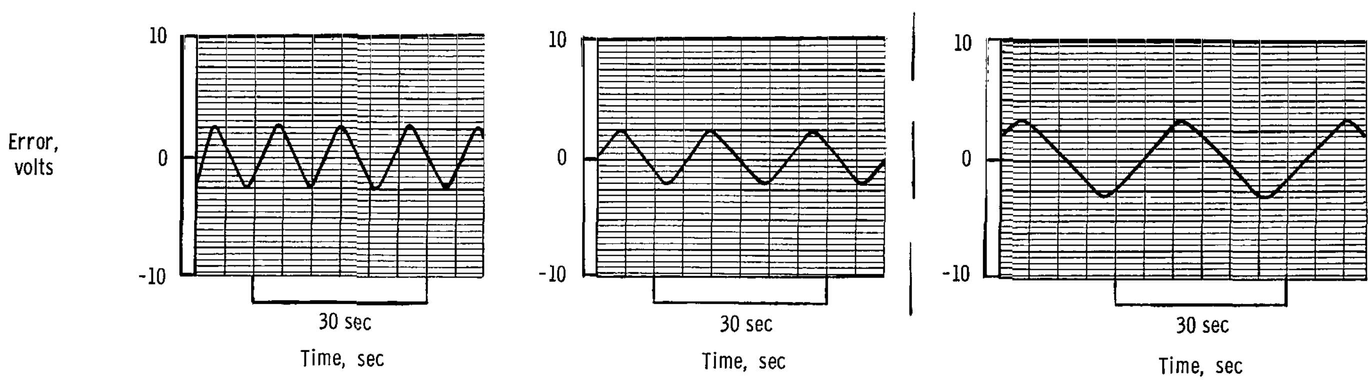
(e) Torque level, ±1 volt, task 3.

Figure 17.- Dynamic response of analog pilot in closed loop system with gains obtained from pilot B.



(a) ±1-volt limit; task 1.

(b) ±1-volt limit; task 2.

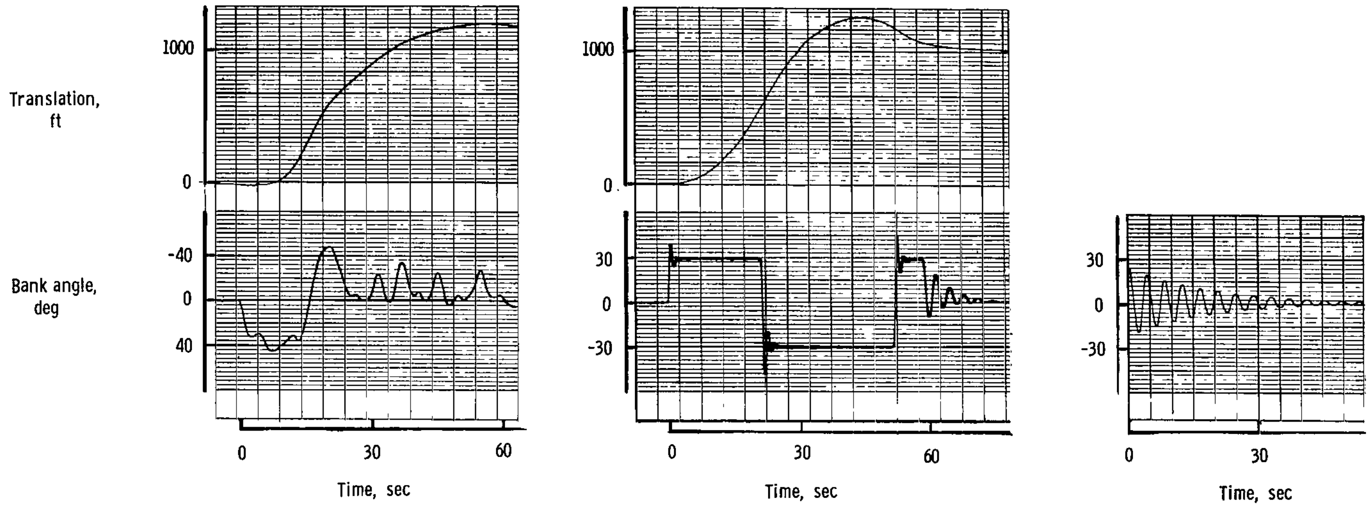


(c) Torque level, ±3 volts, task 3.

(d) Torque level, ±2 volts, task 3.

(e) Torque level, ±1 volt, task 3.

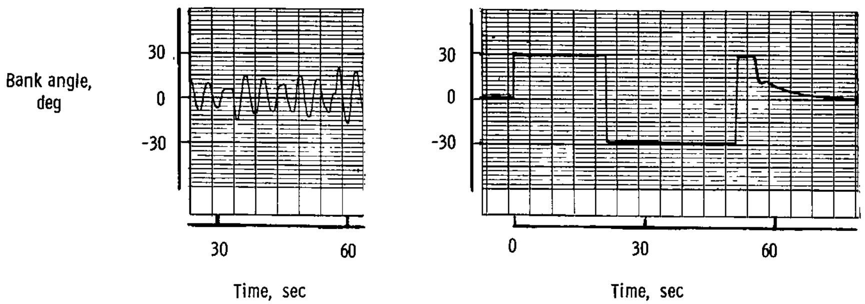
Figure 18.- Dynamic response of analog pilot in closed loop system with gains obtained from pilot D.



(a) Pilot control.

(b) Fixed gain simulation with inner loop. $K_1K = 1.01$; $A = 4$; $K_2 = 30$.

(c) Fixed gain simulation. $K_1K = 6.5$; $A = 6$; $K_2 = 6$.



(d) Fixed gain simulation with K_1 of inner loop equals 0 at times. $K_1K = 6.5$; $A = 6$; $K_2 = 6$.

(e) Fixed gain simulation without inner loop. $K_1K = 1.01$; $A = 4$; $K_2 = 30$.

Figure 19.- Dynamic response of pilot control and fixed gain simulation of multiloop problem.

NASA-Langley, 1965 L-4034

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